A METHOD FOR DEVELOPING A TRIPLE-BOTTOM-LINE BUSINESS CASE FOR THE IMPLEMENTATION OF ALTERNATIVE FUELS AND TECHNOLOGY

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A METHOD FOR DEVELOPING A TRIPLE-BOTTOM-LINE BUSINESS CASE FOR THE IMPLEMENTATION OF ALTERNATIVE FUELS AND TECHNOLOGY

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NOMENCLATURE

List of Abbreviations

B100	Pure Biodiesel
B20	20% Biodiesel Blend
CARB	California Air Resources Board
CFFP	Clean Fuel Fleet Program
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSF	Catalyzed Soot Filter
CWI	Cummins Westport Inc.
DEG	Diesel Equivalent Gallon
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
E85	85% Ethanol and 15% Gasoline
ED	Ethanol and Diesel Emulsion
EPA	Environmental Protection Agency

EPACT	Energy Policy Act
GHG	Greenhouse Gas
GWP	Global Warming Potential
HC	Hydrocarbon
HDDV	Heavy Duty Diesel Vehicle
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MBT	Michigan Business Tax
MMBTU	Million BTU
NAAQS	National Ambient Air Quality Standards
NG	Natural Gas
NGV	Natural Gas Vehicle
NO	Nitrous Monoxide
NO_X	Nitrous Oxides
NREL	National Renewable Energy Laboratory
PM	Particulate Matter
RVP	Ried Vapor Pressure

SO	Sulphur Monoxide
SO_X	Sulphur Oxides
TBL	Triple Bottom Line
THC	Total Hydrocarbons
UDDS	Urban Dynamometer Driving Schedule
US	United States of America
VMT	Vehicle Miles Traveled

List of Symbols

$comp_{gal/day}$	Gallons produced by compressor per day
$Cost_{capital}$	Capital cost for vehicles and facility
$Cost_{comp}$	The cost of the CNG compressors
$Cost_{Dispenser}$	The dispenser cost for CNG refueling station
$Cost_{Equipment}$	The total equipment cost for CNG refueling equipment
$Cost_{Filter}$	The filter cost for CNG refueling station
$Cost_{Install}$	The cost of installation for CNG refueling station
$Cost_{maintenance}$	The yearly cost of maintenance for CNG refueling station

$Cost_{operation}$	The yearly cost of operating the CNG refueling station
$Cost_{Storage}$	The cost of ground storage for CNG refueling Station
$Cost_{sq}$	The sequencer cost for CNG refueling station
Cp_{NG}	The specific heat of natural gas
E_{rate}	The electric rate paid to the utility company
$incost_{vehicle}$	The incremental CNG vehicle cost
$\dot{m}_{comp}$	The mass flow rate of the compressors for CNG refueling station
$m_{Storage}$	The total mass of natural gas in the ground storage
mpg_{diesel}	The average miles per gallon for diesel HDDVs
$mpg_{penalty}$	The percentage reduction for a heavy duty NGV versus diesel
NG_{cost}	The cost of natural gas from the utility company
$N_{Dispenser}$	The number of dispensers in the CNG refueling station
N_{comp}	The number of compressors in the CNG refueling station
$N_{S-tanks}$	The number of ground storage tanks in the CNG refueling station
$N_{vehicles}$	The number of vehicles in the proposed CNG refueling system
$N_{miles/yr}$	The total number of miles driven per year by the proposed system
$N_{F-Tanks}$	The number of fuel tanks per vehicle
$PropertyTax_{Facility}$	The property tax owed for the CNG refueling facility

$PropertyTax_{Vehicle}$	The property tax owed for the CNG vehicles
$TaxCredit_{Fuel}$	The tax credit from alternative fuel use
$TaxCredit_{Property}$	The total tax credit from facilities and vehicles
$TaxCredit_{Vehicle}$	The tax credit from alternative fuel vehicles
$TaxCredit_{facility}$	The tax credit for alternative fuel refueling facilities
$Savings_{annual}$	The annual economic savings for the CNG refueling system
$scfm_T$	The total volumetric flow rate for the CNG refueling station
$SimplePayback$	The economic simple payback period
$TBLsavings_{annual}$	The annual Triple-Bottom-Line saving
$TBLsimplePayback$	The Triple-Bottom-Line simple payback
U_{comp}	The utilization of the compressor
$Value_{Taxable}$	The value of property which is taxable
$Saving_{mile}$	The savings per mile for the natural gas vehicles
ρ_{NG}	The density of natural gas

SUMMARY

Alternative fuels and technologies for truckload carriers can provide significant environmental and social benefits over traditional heavy duty diesel vehicles by reducing petroleum-based fuel consumption and vehicle tailpipe emissions. These alternative fuels and technologies, however, often carry a cost premium or require significant capital investment. Dedicating vehicles, equipment, and infrastructure to an alternative fuel or technology also represents a significant risk in the extremely volatile trucking business. A Triple-Bottom-Line analysis, which includes economic, social, and environmental impacts of an alternative fuel or technology will strengthen the business case by incorporating the benefits of emissions reduction. A stronger business case will promote the use of alternative fuels and technologies while mitigating the risk.

This thesis proposes a method for identifying alternative fuels and technologies that provide the best Triple-Bottom-Line benefit and provides a structure for modeling the emissions of the target application, quantifies the value of emissions reduction, and constructs a Triple-Bottom-Line business case. The Triple-Bottom-Line business case proposed by this method is incremental. It presupposes an existing or planned truckload carrier business already exists and only investigates the changes which occur with implementation of an alternative fuel or technology. This method may be useful for any carrier business or any company with an extensive shipping and logistics network. A case study, which was created for large automotive manufacturer, details the Triple-Bottom-Line business case for an on-site compressed natural refueling system and vehicles.

CHAPTER 1 INTRODUCTION

1.1 Objective of Thesis

The objective of this thesis is to develop a method for creating a business case for the implementation of an alternative fuel or technology in shipping and logistic networks, specifically to incorporate economic, environmental, and social impacts to strengthen the business case for the use of alternative fuels and technology in on-road heavy duty vehicles.

1.2 Overview of the Problem

Most alternative fuels carry a cost premium or are cost neutral, when compared to gasoline or diesel, and often require significant vehicle or infrastructure investment. Alternative technologies that reduce tailpipe emissions usually decrease vehicle efficiency which results in increased fuel consumption and operating cost. An alternative technology which increases vehicle efficiency typically requires a significant capital investment and does not recoup investment capital quickly. For these reasons, the implementation of an alternative fuel or technology in shipping and logistics networks is typically unfeasible from an economic perspective. Over-the-road heavy duty diesel vehicles, HDDV, represent a large percentage of most large shipping and logistics networks. These shipments are usually made by trucking companies, also referred to as carriers, which can range from single trucks owned by the driver to companies with large national fleets. In either case, the creation of a positive business case is necessary before a carrier can confidently invest in an alternative fuels or technology.

An alternative fuel is defined as any fuel determined to be 'substantially not petroleum' and yielding ‘substantial energy security benefits and substantial environmental benefits'

(Energy Policy Act of 2005) . Alternative technologies are defined in an analogous sense as any vehicle technology designed to increase efficiency, reduce tailpipe emissions, or utilize an alternative fuel or power source. Therefore, an economic business case for an alternative fuel or technology is strengthened by including the social and environmental benefits obtained via reduced petroleum consumption and vehicle emissions. This approach falls under the category of Triple-Bottom-Line (TBL) accounting, first outlined by John Elkington in the 1998 book '*Cannibals with Forks: the Triple Bottom Line of 21st Century Business'.* The TBL standard has become the dominant approach to public sector full cost accounting since it was ratified in 2007 by the United Nations International Council for Local Environmental Initiatives, an international association of local government organizations that have made a commitment to sustainable development. The TBL approach used in this analysis, however, is tailored for the private sector which requires a stronger emphasis on the economic impact. The shipping and logistics network of a large automotive manufacturer is used as a case study in this paper.

The automotive manufacturer has several key motivators for exploring the use of alternative fuels and technologies for their truckload carriers. Their primary economic interest is to improve the cost effectiveness of their shipping and logistics network, specifically the inbound deliveries which originate either from component suppliers or deliveries between thier manufacturing facilities. These deliveries are typically made by Class 7, Class 8, or Class 9 HDDV which are owned and operated by outside carriers. The company does, however, have a small fleet which it operates independently. Freight costs are typically structured as a flat rate plus a fuel surcharge. The fuel surcharge is then based on a negotiated per-mile rate. As a result, any decrease in fuel consumption by the carrier can benefit the company by lowering the agreed upon fuel surcharge rate. Because surcharge rates are often brokered when the price of diesel spikes, reducing petroleum dependence carries an additional economic incentive. The automotive manufacturer has set aggressive targets for reducing their environmental footprint and greenhouse gas emissions. A methodology for identifying, evaluating and implementing alternative fuels and technology will aide the automotive manufacturer in accomplishing these goals.

1.3 Proposed Solution

This section will present the proposed methodology for selecting top performing alternative fuels and technologies and the creation of a TBL business cases. An overview of the strongest business case created for a large automotive manufacturer under current market conditions is also presented.

1.3.1 Proposed Methodology

The proposed methodology, shown in Figure 1.1, can be broken down into five steps: performing a literature review, identifying candidate fuels and technologies, eliminating candidates, evaluating candidates, and creating a TBL business case for the top performing candidates. The initial focus of the literature review is to generate a list of all possible alternative fuels and technologies suitable for the target application. The focus of the literature survey then shifts to an in-depth cost and benefit analysis after the number of candidates has been sufficiently reduced. After top candidates are identified, a full TBL analysis is performed. It is important to note the process of identifying the alternative fuel or technology with the strongest TBL business case is an iterative process since the optimal level of vehicle and facility investment is difficult to predict. The following sections will outline each step in more detail.

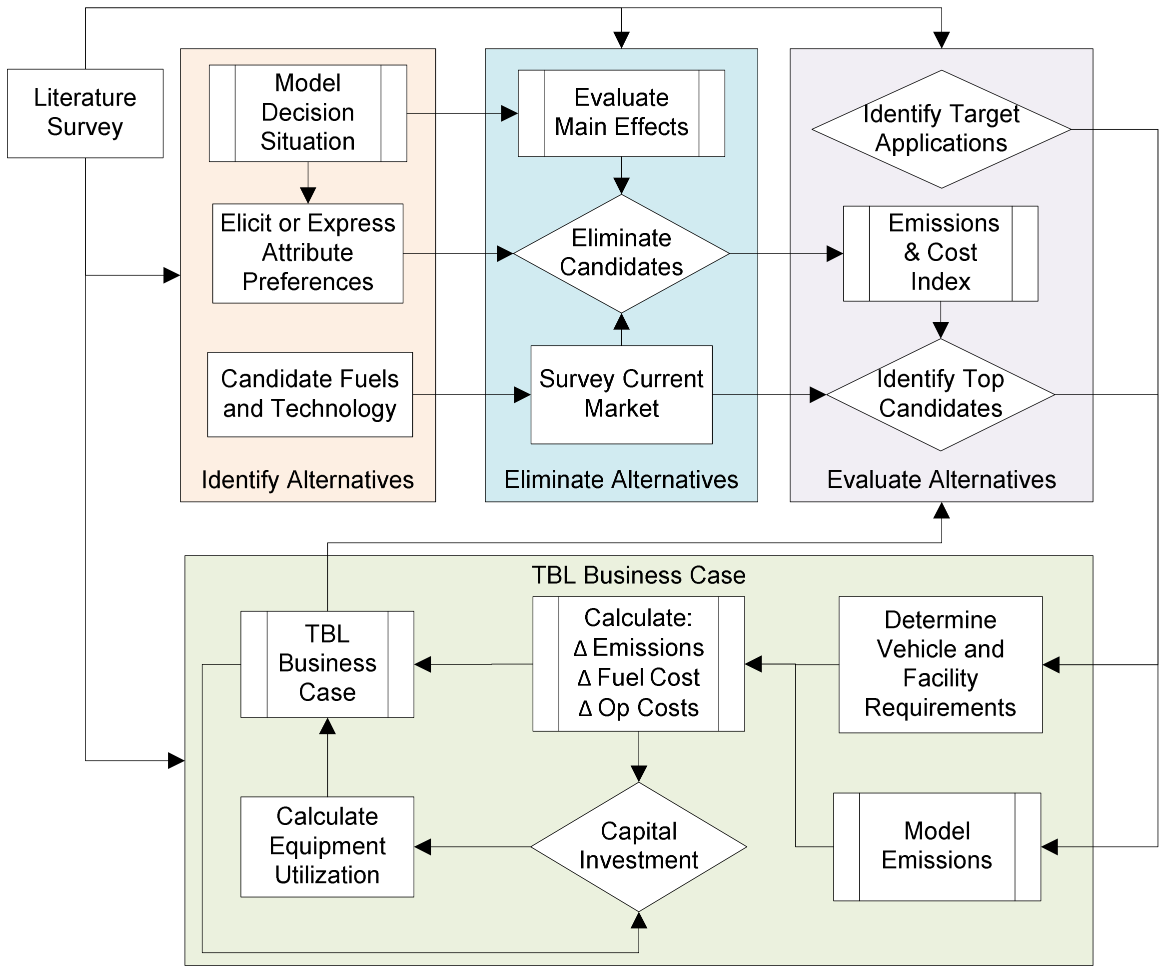


Figure 1.1 Flow Diagram for Decision Situation

<u>1.3.1.1 Literature Survey</u>

The initial literature survey provides a broad list of alternative fuels and technologies available for the target application of interest by finding current examples of their use. In the case of the large automotive manufacturer, the specific application is the replacement or augmentation of traditional HDDV for their inbound delivery vehicles. In depth technical data is not necessary at this point, so EPA newsletters, trade organizations, press releases, the California Clean Air Board, and engine manufacturers are all adequate sources to find examples of alternative fuel and technology applications. Since emissions are of primary concern in urban areas, most of the current applications of alternatives fuels and technologies for HDDV revolve around urban transit busses. Alternative fuels and technologies for diesel powered urban transit busses, however, are usually applicable to Class 8 and Class 9 tractor trailers in most situations.

The second phase of the literature survey provides the necessary information to model the overall decision situation, determine the key metrics, evaluate the main effects, and determine the vehicle and facility requirements for the candidate fuels and technologies. Data gathered during the literature survey is also used to quantify the societal and environmental effects of tailpipe emissions during the final TBL analysis. The literature survey performed for the large automotive manufacturer's application is presented in Chapter 2.

1.3.1.2 Identifying Candidate Alternative Fuels and Technologies

A direct survey is conducted of the truckload carriers for the target application in order to provide additional information on availability, performance, costs, experience, and infrastructure relating to alternative fuels and technology as well as providing baseline information on the current vehicles in operation. The data gathered is used to further reduce the number of candidate fuels and technologies. This survey also serves as a method for gauging the level of interest in alternative fuels and technology and helps to identifying possible implementation partners. The survey results and analysis of the large automotive manufacturer's carrier network are given in Chapter 3.

In order to identify alternatives, the scope of a specific application is defined using a decision model. The decision model is composed of objectives, key decisions, uncertain events, intermediate calculations, and measures of effectiveness for the specific application.

The decision model is used to elicit the decision maker's preferences and requirements, which are necessary to eliminate candidate fuels and technologies in subsequent steps. A detailed explanation of the decision model is given in Chapter 4.

1.3.1.3 Eliminate Candidate Fuels and Technologies

The information gathered in the literature survey is used in conjunction with the decision model to create a Decision Matrix. This matrix predicts the impact that each alternative fuel or technology will have on measures of effectiveness defined in the decision model. The Decision Matrix is then used in conjunction with elicited user preferences and requirements to eliminate candidates which are not viable. In the case of the large automotive manufacturer, their TBL analysis is for short-term implementation of an alternative fuel or technology. This eliminates all fuels and technologies not readily available in the geographic area of interest at the time the analysis is performed.

1.3.1.4 Evaluate Candidate Fuels and Technologies

The remaining candidates are evaluated using an emissions index and a cost index. These indexes rank the relative effect that alternative fuels and technologies have on the measures of effectiveness, derived in the decision model. Candidates that rank higher in the indexes are more likely to produce a positive TBL business case. These indexes only consider a small portion of actual impacts of switching to an alternative fuel or technology. The approximation is useful for eliminating candidates that will clearly not produce required results and for identifying candidates needing further analysis.

The emissions index for alternative fuels and technology is created utilizing a percentage change in tailpipe emissions for equal distance traveled, which is expected when switching the target application to an alternative fuel. The environmental index is created using the information gathered from technical papers which measure the tail pipe emissions of the target application on a chassis dynamometer. Tests typically involve similar vehicles running standard fuel and alternative fuels under standard drive cycles. In the case of the large automotive manufacturer, studies which compared the emissions of on-road HDDV running convention diesel and alternative fuels under the standard Urban Dynamometer Driving Schedule, UDDS, are used whenever possible. Alternative technologies are incorporated into the emissions index in a similar manner. The cost index for alternative fuels is created by relating the cost per megajoule for the alternative fuel versus the standard diesel. The cost index serves as only a preliminary estimate of the expected change in fuel cost because it does not account for the changes in efficiency which may accompany an alternative fuel. The cost index for alternative technologies is based on the effectiveness of reducing emissions on a dollar per ton basis.

1.3.1.5 Develop TBL Business Case

The change in fuel cost, value of emissions savings, and change in operating costs are related on a per mile basis by considering all practical aspects of operating an alternative fuel or technology. These impacts are identified in the literature survey and include changes in vehicle efficiencies, maintenance schedules, tailpipe emissions, vehicle range, taxes and equipment.

Relating costs and savings on a per mile basis allow benefits to be evaluated independent from the implementation scale. The annual costs and benefits are ultimately dependant on the number of miles traveled per year, which is a function of the capital investment in vehicles and facilities. Current data on vehicle and facility costs are gathered through direct contact with suppliers. The annual mileage capacity, as a function of capital investment, is calculated and the investment is then optimized for the quickest TBL simple payback. A detailed explanation of the methodology used to create a TBL business case is given in Chapter 5.

In the case of the large automotive manufacturer, on-site compressed natural gas, CNG, produces the most compelling TBL business case under current market conditions. An overview of the proposed business case is given in section 1.3.2 and detailed explanation of all relevant calculations is given in Chapter 6.

1.3.2 Case Study – On-site Compressed Natural Gas

If natural gas is purchased from utility companies and compressed onsite, the price ratio between equivalent amounts of diesel and natural gas, on an energy basis, provides a tremendous opportunity for fuel cost savings. There is a significant amount of capital investment required for a CNG refueling station and CNG vehicles, but this cost is offset by large government tax incentives. Running CNG also provides substantial environmental and social benefits via reduced tailpipe emissions.

The proposed on-site CNG system, which includes refueling facilities and 22 CNG vehicles, requires a minimum capital investment of 1.3 million dollars. This cost is offset in the first year by tax credits in the amount of $620,000 for alternative fuel vehicles and facilities. The refueling station supports 22 vehicles, each of which run between 300 and 350 miles per day. Based on current fuel prices, the expected fuel saving is $0.19 per mile and there is a current tax credit for natural gas which amounts to $0.06 per mile. The system can support approximately 2.3 million miles per year, which equates to an annual savings of 420 thousand dollars per year. However, the fuel tax credit is set to expire in 2010, which will result in an annual savings of $190,000 per year.

The vehicles are dedicated to CNG and have a range of approximately 380 miles. This fact limits them to short haul shipping lanes which originate or terminate near the central refueling station. The large automotive manufacturer has an abundance of qualifying lanes due to high volumes of shipments between manufacturing facilities which are located in close proximity to each other. The business case could be replicated many times, but the extent to which this system can be expanded in the company's network is not known. This business case does not apply to truckload carriers which do not have a guaranteed supply of short haul business.

With the incentives in the current tax code, the simple payback for the proposed refueling station is 1.6 years with an internal rate of return, abbreviated as IRR, of 36%. Without the tax incentives, the simple payback is 6.9 years with an IRR of 11%. Given the inherent risk involved, tax incentives are crucial for the CNG business case if it is viewed purely from an economic standpoint. With the incentives in the current tax code, the TBL simple payback for the proposed refueling station is 0.9 years with an IRR of 73%. The purpose of alternative fuel tax credits, however, may be interpreted as money paid to subsidize the environmental and social benefits of alternative fuels and promote their use. A TBL business case including tax incentives may count the value of the emissions savings twice. The TBL simple payback without tax incentives is 2.67 years with an IRR of 43%, which is still overwhelmingly positive.

The economic business case with tax incentives is one year faster, than the TBL business case without tax incentive. This indicates that either the government is paying a premium for economic and social benefits in an effort to encourage their use, or the dollar values used for emissions abatement in the TBL business case are too small. Since the fuel tax credit is currently set to expire during the useful lifespan of the refueling facility, the IRR of the TBL analysis is still 10% higher than the economic case despite having a longer payback period. Since the IRR is a better metric for the strength of a business case, the TBL analysis still provides an improvement to the CNG business case even if tax incentives are not included.

CHAPTER 2 LITERATURE REVIEW

This literature review is divided into two sections; one section examines the social and environmental impacts of emissions and the other section examines candidate alternative fuels and technologies. The social and environmental impacts include sources of mobile emissions, types of emissions considered, environmental and sociological effects. The alternative fuels and technologies section gives an overview of the potential candidates for the large automotive manufacturer's specific application and provides the necessary information to complete the emissions and cost indices as well as the decision matrix.

2.1 Social and Environmental Impacts of Emissions

The emissions considered in this TBL method are those defined by the EPA as criteria pollutants. There are six criteria air pollutants regulated by EPA: carbon monoxide, nitrogen oxides, lead, sulfur dioxides, ozone, and particulates, all of which have been determined to be hazardous to human health and the environment (EA Engineering, Science, and Technolgy, INC., 1997). These emissions, with the exception of lead, are considered in the TBL business analysis for alternative fuels and technology. Lead is not considered because it is not associated with diesel tailpipe emissions. Carbon dioxide is considered in the TBL analysis because of the significant impact it has on the environment. Section 2.1.2 details different perational sources of vehicle emissions, Section 2.1.2 describes each pollutant considered in the analysis, and Section 2.1.3 describes the potential environmental and health effects of each ollutant.

2.1.1 Operational Emission Sources

2.1.1.1 Evaporative Emissions

Fuels which vaporize at warm ambient temperatures cause increased pressure inside the vehicle's fuel system. Carbon canisters are often incorporated into the fuel systems to capture vapor, but the carbon canister cannot handle the large amount of vapor generated in some situations and the fuel system automatically vents excess vapor. This is a particular problem for gasoline powered vehicles. Diesel vehicles, however, do not have significant evaporative emissions because diesel fuel vaporizes much less readily (New York State Energy Research and Development Authority, 1997). Some volatile alternative fuels, such as propane or ethanol, have significant evaporative emissions (Beer, et al., 2001).

Diurnal Emissions are a type of evaporative emissions which occur during the day while a vehicle is not being used. Rising temperatures during the day heat the fuel in a vehicle's tank, which causes the pressure to rise and eventually vent to atmosphere (New York State Energy Research and Development Authority, 1997). Running Losses are a type of evaporative emissions released from the fuel system when the car is running. In this case, the heat from the engine heats fuel under the hood. Since most vehicles have fuel-injection systems that recirculate large amounts of fuel from the engine compartment to the fuel tank, the fuel tank becomes heated (New York State Energy Research and Development Authority, 1997). Excess vapor must then be vented. Hot Soak is a type of evaporative emissions which occurs during the period following vehicle operation. Since the engine and fuel system are hot, fuel evaporation continues when the car is parked (New York State Energy Research and Development Authority, 1997).

Refueling Loss Emissions are evaporative emissions which are released to the atmosphere whenever a vehicle is refueled. Fuel vapors are first released from the vehicle fuel tank when the tank cap is removed. Refueling emissions also occur during refueling when fuel vapors inside the tank are displaced out through the filler tube by incoming fuel. These vapors are recovered if the dispenser has a Stage II refueling system where vapors are routed to the service-station tank. Refueling emissions also occur when tanks are overfilled, when fuel is spilled from the nozzle between the dispenser and the vehicle, and when fuel evaporates from the wetted portions of the nozzle after refueling (New York State Energy Research and Development Authority, 1997).

2.1.1.2 Exhaust Emission

The combustion process results in emissions of volatile organic compounds, nitrous oxides, particulate matter, carbon monoxide, carbon dioxide, sulfur oxides, water, and other trace compounds which are released from the tailpipe while a vehicle is operating. Two different operation modes, cold start and running exhaust, effects the composition of the tailpipe emissions. Cold start describes the first few minutes of vehicle operation which results in higher emissions due to the fact that the emissions control equipment has not yet reached its optimal operating temperature. Running exhaust describes the emissions of the vehicle during driving and idling after the vehicle is warmed up. In general, the less volatile and more aromatic the fuel, the higher the exhaust particle emissions and oxygenated fuels produce fewer particles due to more complete combustion (Beer, et al., 2001). The presence of impurities such as sulfur will also result in extra particle formation

2.1.1.3 Greenhouse Gas Emissions

The Kyoto Protocol defines carbon dioxide, nitrous oxide, hydrofluorocarbons, methane, sulfur hexafluoride, and perfluorocarbons as greenhouse gases. The Kyoto Protocol has adopted the concept of a global warming potential (GWP) as the basis for defining equivalences between emissions of different greenhouse gases by expressing them in carbon dioxide equivalents. The GWP reflect the different extent to which gases absorb infrared radiation and the differences in the time scales on which the gases are removed from the atmosphere. The Kyoto Protocol requires calculations of greenhouse gases to be made on the basis of fossil-fuel derived carbon dioxide (Beer, et al., 2001).

The Kyoto Protocol requires calculations of greenhouse gases to be made on the basis of fossil-fuel derived carbon dioxide. Carbon dioxide generated as a result of the combustion of a renewable fuel is not included in greenhouse gas inventories. This includes fuels made from biomass because carbon dioxide emitted during combustion of the fuel is offset by that absorbed by the plant from the atmosphere during growth. Greenhouse debits may arise, however, due to the use of agricultural chemicals, fueling of farm machinery, transport of the crop, processing of the crop, drying of liquid wastes and transport of the fuel. Denitrification of fertilizers applied to the crop is also a major problem because nitrogen oxides will be emitted, which has a high GWP (Beer, et al., 2001).

2.1.2 Types of Emissions

Under the Clean Air Act, the US EPA is responsible for setting National Ambient Air Quality Standards (NAAQS) for the six criteria pollutants. Of these pollutants, ozone is not attributable to direct emissions but is instead a function of ozone precursor emissions. Oxides of nitrogen and volatile organic compounds are regulated as precursors for ozone (M.J. Bradley & Associates, Inc., February 2000). Vehicle exhaust is not a significant source of lead, so it will not be considered in this analysis. Carbon dioxide is not considered harmful to health, but is included in this analysis because of its environmental impact.

2.1.2.1 Nitrous Oxides

Nitrous oxides are formed in combustion reactions when nitrogen and oxygen atoms react under high-pressure and temperature. Ozone is formed in the atmosphere when nitrous oxide and hydrocarbons react in the presence of sunlight. Nitrous oxides also contribute to the formation of acid rain (EA Engineering, Science, and Technolgy, INC., 1997). The Intergovernmental Panel on Climate Change estimates the 100-year global warming potential of nitrous oxide to be 296 times that of carbon dioxide (Delucchi, 2006). Nitrous oxides are also denoted as NO_X.

2.1.2.2 Sulfur Oxides

Sulfur oxides are formed when fuel containing sulfur, such as coal and oil, is burned. Sulfur dioxide dissolves in water vapor to form acid, and interacts with other gases and particles in the air to form sulfates and other products that can be harmful to people and their environment. The Intergovernmental Panel on Climate Change does not currently compute a global warming potential for sulfur oxides (Delucchi, 2006). Sulfur oxides are also denoted as SO_X.

2.1.2.3 Carbon Dioxide

Carbon dioxide, along with water, is the primary product of combustion for a hydrocarbon fuel. Carbon dioxide is also produced by all animals, plants, fungi and microorganisms during respiration and is used by plants during photosynthesis to make sugars. Carbon dioxide is an important greenhouse gas because it transmits visible light but absorbs infrared radiation. The Intergovernmental Panel on Climate Change currently uses carbon dioxide as its baseline for the 100-year global warming potential index, and therefore assigns it a value of 1 (Delucchi, 2006). Carbon dioxide is also denoted as CO_2.

2.1.2.4 Carbon Monoxide

Carbon monoxide is a colorless, odorless gas produced by incomplete combustion of hydrocarbon fuels. Incomplete combustion is an issue for internal combustions engines because the fuel has a limited duration in which to burn and is combusted in a relatively small space with high peak flame temperatures (M.J. Bradley & Associates, Inc., February 2000). Carbon monoxide emissions from vehicles are highest during vehicle warm-up in cold weather (EA Engineering, Science, and Technolgy, INC., 1997). Carbon monoxide does not contribute to ozone formation, although it is a greenhouse gas. The Intergovernmental Panel on Climate Change estimates the 100-year global warming potential of carbon monoxide as 1.6 times that of carbon dioxide (Delucchi, 2006). Carbon monoxide is also denoted as CO.

2.1.2.5 Particulate Matter

Several things can initiate the formation of carbon particulate emissions, either separately or in combination, including incomplete combustion, misfiring, lubricant combustion and impurities in the fuel (M.J. Bradley & Associates, Inc., February 2000). Diesel engines produce relatively large amounts of the fine particulates that are of special concern to health researchers (EA Engineering, Science, and Technolgy, INC., 1997). Particulate matter from internal combustion engines is composed of a combination of carbon particles, on the surface of which organic compounds are adsorbed. If there is sulfur in the fuel, sulfur compounds will also be present in the particulate along with some metals from the fuel, lubricating oil and wear products. The organic fraction of particulate matter is dependent upon the fuel combusted, its' combustion residence time, combustion temperature, engine lubricant, and whether an oxidation catalyst or regenerative particulate trap is installed. The Intergovernmental Panel on Climate Change does not currently compute a global warming potential for particulate matter emissions (Delucchi, 2006). Particulate matter is also denoted as PM or PMXX, where XX denotes the largest particle size considered in microns.

2.1.2.6 Hydrocarbons and Volatile Organic Compounds

Hydrocarbons are emissions of unburned or partially burned fuel. Exhaust hydrocarbon emissions occur from incomplete fuel combustion in the engine, but additional hydrocarbon emissions can result from evaporative emissions. The primary concern with hydrocarbons emissions is the potential to create ground-level ozone (EA Engineering, Science, and Technolgy, INC., 1997). Almost all unburned hydrocarbons contain a small fraction of methane, except for natural gas. The vast majority of unburned hydrocarbons in natural gas are methane for obvious reasons. Methane is nontoxic and has very little involvement in forming ozone or other pollutants when compared with most other typical hydrocarbons, so some emissions regulations are written to include only non-methane hydrocarbons (EA Engineering, Science, and Technolgy, INC., 1997). The Intergovernmental Panel on Climate Change (IPCC) estimates the 100-year global warming potential of methane and non-methane hydrocarbons as 23 and 3.66 times that of carbon dioxide respectively (Delucchi, 2006). The total hydrocarbon emissions are denoted as THC or HC.

Volatile organic compounds, also referred to as VOC, are defined in a regulatory sense as any compound of carbon that participates in atmospheric photochemical reactions (M.J. Bradley & Associates, Inc., February 2000). Examples of volatile organic compound emissions from vehicles include all evaporative and refueling emissions. Volatile organic compounds also include partially combusted fuel constituents (New York State Energy Research and

Development Authority, 1997). Hydrocarbons can generally be used synonymously with the volatile organic compounds designation. The exception to this rule occurs in vehicles and internal combustion equipment that combusts natural gas. Because methane is not considered a VOC, HC emission values from natural gas vehicles are usually divided into methane and non-methane hydrocarbon (M.J. Bradley & Associates, Inc., February 2000).

2.1.3 Health Impacts of Diesel Emissions

Short term health effects of inhalation exposure to diesel exhaust include eye, throat and bronchi irritation, neurophysiological symptoms such as headaches, light-headedness, fatigue, abdominal discomfort and nausea and respiratory symptoms such as coughing and phlegm. (Edwards, et al., 2005). Evidence for symptoms associated with diesel exhaust exposure, including eye and mucus membrane irritation, cough, phlegm, dyspnea, headache, light-headedness, dizziness, nausea, and odor annoyance, comes largely from epidemiologic studies of workers in industries where diesel-powered equipment was used (Lloyd, et al., 2001). Long term health effects of diesel exhaust are associated with particulate matter, carbon monoxide, and the ground level ozone, which is produced by volatile organic compounds and nitrogen oxides.

2.1.3.1 Particulate Matter

The adsorbed organic fraction of particulate matter poses the largest toxic risk because the carbon particles are generally less than 2.5 microns which enables them to remain airborne. If inhaled into the lungs, the organic compounds can be absorbed and potentially cause damage (M.J. Bradley & Associates, Inc., February 2000). Long term exposure to diesel exhaust particles poses the highest cancer risk of any toxic air contaminant evaluated by Office of Environmental Health Hazard Assessment and the Air Resources Board estimated that approximately 70% of the cancer risk that the average Californian faces from breathing toxic air pollutants stems from diesel exhaust particles (Edwards, et al., 2005). A consistent causal relationship between occupational diesel exhaust exposure and lung cancer was found in more than 30 human epidemiologic studies. On average, long-term occupational exposures to diesel exhaust were associated with an increase of approximately 40% in the relative risk of lung cancer. Population-based case-control studies identified statistically significant increases in lung cancer risk for truck drivers, railroad workers, and heavy equipment operators. These increases were consistent with self-reported diesel exhaust exposures (Lloyd, et al., 2001).

Health effects associated with short-term exposure to particulate matter have been indicated by epidemiologic studies showing associations between exposure and increased hospital admissions for ischemic heart disease, heart failure, respiratory disease, including chronic obstructive pulmonary disease and pneumonia (United States Environmental Protection Agency, 2007). Additional studies have associated changes in heart rate and/or heart rhythm in addition to changes in blood characteristics. Short-term term exposure to particulate matter is also associated with increases in total and cardio respiratory mortality (United States Environmental Protection Agency, 2007). Epidemiological evidence indicates that decreasing particle emissions reduces morbidity and reduces hospital admissions as a result of respiratory illness. At present, diesel engines are a major source of fine particles – diesel exhaust releases particles at a rate about 20 times greater than that from petrol-fuelled vehicles (Beer, et al., 2001).

2.1.3.2 Ground Level Ozone

Ozone is formed as the result of atmospheric physical and chemical processes involving volatile organic compounds and nitrogen oxides (EA Engineering, Science, and Technolgy, INC., 1997). While much has been accomplished in reducing ozone levels, ground-level ozone remains a pervasive pollution problem in many areas of the United States. Exposure to ozone has been linked to a number of health effects, including significant decreases in lung function, inflammation of the airways, and increased respiratory symptoms, such as cough and pain when taking a deep breath. Exposure can also aggravate lung diseases such as asthma, leading to increased medication use and increased hospital admissions and emergency room visits (United States Environmental Protection Agency, 2007).

2.1.3.3 Carbon Monoxide Health Impacts

Carbon monoxide is poisonous if inhaled, entering the bloodstream through the lungs and forming carboxyhemoglobin, a compound that inhibits the blood's capacity to carry oxygen to organs and tissues. Carbon monoxide can impair exercise capacity, visual perception, manual dexterity, and learning functions (EA Engineering, Science, and Technolgy, INC., 1997). Carbon monoxide is generally a local emission issue with the impact typically occurring in low lying areas such as urban canyons. Carbon monoxide affects the ability of blood to carry oxygen and results in impaired cardiovascular, pulmonary and nervous systems. Excess carbon monoxide emissions are usually associated with cold engine startups and engine operation in open loop mode (M.J. Bradley & Associates, Inc., February 2000).

2.1.4 Environmental Impacts of Diesel Emissions

Reactivity of vehicular emissions is the potential of emissions constituents to combine chemically with each other to form new compounds. The relative concentration of these emissions constituents is important in determining the rate and extent of the reaction. Some of the important consequences of reactivity include formation of ozone, smog, and acid rain.

Smog is a brownish haze in the air that forms in highly polluted metropolitan areas. Its main unhealthy ingredient is ground-level ozone. Sunlight and warm temperatures are conducive to smog formation. (New York State Energy Research and Development Authority, 1997).

Acid rain is rainwater, snow, fog, and other forms of precipitation that contain mild solutions of sulfuric and nitric acids. Combustion emissions of note in this regard include sulfur monoxide (SO), the primary source of which is coal fired power plants, and NO. Acid rain usually forms high in the clouds where SO and NO react with water and oxidants, forming a mild solution of sulfuric and nitric acids. Sunlight increases the rate of these reactions. Acid rain causes damage to lake and forest habitats, as well as significant damage to building exteriors

Ozone also affects vegetation and ecosystems, leading to reductions in agricultural crop and commercial forest yields, reduced growth and survivability of tree seedlings, and increased plant susceptibility to disease, pests, and other environmental stresses (e.g., harsh weather). In long-lived species, these effects may become evident only after several years or even decades and may result in long-term effects on forest ecosystems. Ground level ozone injury to trees and plants can lead to a decrease in the natural beauty of our national parks and recreation areas. (United States Environmental Protection Agency, 2007). Visibility degradation, or haze, is another effect of reactive exhaust emissions (Lloyd, et al., 2001)

The effect of greenhouse gasses is a warming influence caused by emissions which are very efficient absorbers and radiators of the infrared radiation. The light-absorbing properties of diesel exhaust also affect the earth's radiation balance. The transportation sector is currently responsible for approximately 26% of greenhouse gas emissions in the United States and, due to increased demand for gasoline and diesel fuel, is expected to be one of the fastest growing sources of greenhouse gas emissions in the foreseeable future (Lloyd, et al., 2001).

2.2 Candidate Alternative Fuels and Technologies for HDDV

The Energy Policy Act of 2005 (EPACT), the Clean Fuel Fleet Program (CFFP), and the Federal Clean Cities Program are key drivers for the alternative fuels and technology market. State and local agencies have also imposed various mandates, incentives and policies that can affect alternative fuel and technology usage. One of the goals of EPACT is to displace 30% of US petroleum use with alternative fuels by 2010 (Energy Policy Act of 2005). This goal is not expected to be achievable with expected future alternative fuel penetration rates.

The candidate alternative fuels and technologies presented in this section are selected based on a broad literature survey of applications involving the replacement of diesel in heavy-duty vehicles. Sources of application information are informal, including EPA factsheets, equipment manufacturer's catalogs and websites, trade organization newsletters, journal articles, news reports and various presentations given by people in industry. Biodiesel, Natural Gas, Ethanol, Methanol, and Liquefied Petroleum Gas were identified as possible fuels for HDDV by the initial literature survey and Hybrid and Clean Diesel are identified as possible alternative technologies. It is important to note that these are broad categories, and there are many subsets within each one. Biodiesel, for example, may be used neat, or mixed with diesel fuel in varying amounts. A literature review of each fuel or technology will be presented in this section including the emissions performance, production method, safety, social benefits, vehicle performance, associated costs, and a summary of the each fuel's overall performance.

2.2.1 Biodiesel

Biodiesel is a fuel composed of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100, and meeting the requirements of the American Society for Testing & Materials D 6751. Stated simply, it is the product of a chemical reaction between the basic feedstock, vegetable oil or animal fat, and alcohol in the presence of a catalyst. The reaction results are a fatty acid alkyl ester the biodiesel and a byproduct called glycerol (Fortenbery, 2005). Table 1 shows the molecular formula and weight for biodiesel derived from soybeans (National Biodiesel Board). The composition, properties, and performance of biodiesel from different feed stocks will vary.

Table 1 Molecular Formula and Weight for Soybean Based Biodiesel

Fatty Acid	Weight Percent	Molar Weight	Formula
Palmitic	12%	270.460	$C_{15}H_{31}CO_2CH_3$
Stearic	5%	298.520	$C_{17}H_{35}CO_2CH_3$
Oleic	25%	296.500	$C_{17}H_{33}CO_2CH_3$
Linoleic	52%	294.480	$CH_3(CH_2)_4CH{=}CHCH_2CH{=}CH(CH_2)_7$
Linolenic	6%	292.460	$CH_3(CH_2CH{=}CH)_3(CH_2)_7CO_2CH_3$
	Average:	292.2	

Biodiesel contains no petroleum, but it can be blended at any level with petroleum diesel to create a biodiesel blend. Biodiesel blends are named according the percent, by volume, of biodiesel which is contained in the fuel. Biodiesel B20, for example, contains 20% pure biodiesel and 80% diesel by volume.

2.2.1.1 Biodiesel Technology

Biodiesel technology revolves around the method of production and impacts of various biodiesel blends. According to the National Biodiesel Board, B20 is currently the most popular and widely available blend of biodiesel, most likely because it can be used in conventional diesel motors without modification. Most auto, engine, and fuel injection equipment companies doing business in the US strongly discourage the use of blends over B20 due to the impacts of higher blends on equipment and fuel systems which have not been thoroughly tested with these high blends, and the higher likelihood of known problems or issues with high blends that are not present or are of lesser importance when using B20 or lower blends. Blends higher than B20 cannot be considered a direct replacement for petroleum diesel fuel and may require significant additional precautions, handling, and maintenance considerations as well as potential fuel system and engine modification. Problems specifically caused by any fuel, including biodiesel or biodiesel blends, are not considered manufacturing defects and generally will not be covered by any engine or fuel injection equipment manufacturer's warranty.

B100 will soften and degrade certain types of elastomers and rubber compounds over time. Using high percent blends can impact fuel system components (primarily fuel hoses and fuel pump seals) that contain compounds incompatible with B100. Manufacturers recommend that natural or butyl rubbers not be allowed to come in contact with pure biodiesel or biodiesel blends higher than B20. Over the past 15 years of use, blends of B20 or lower have not exhibited problematic elastomer degradation and no changes are recommended. If a fuel system does contain these materials and users wish to fuel with blends over B20, replacement with compatible elastomers is needed. In many instances, especially with older equipment, the exact composition of elastomers cannot be obtained and it is recommended they be replaced if using blends over B20 (National Biodiesel Board).

B100, on average, has 7-9% lower energy content (BTU per gallon) than average #2 diesel fuel. Conventional diesel engines convert the energy in biodiesel into work with the same efficiency as standard diesel, so impacts on fuel economy, peak horsepower and peak torque are all directly related to the energy content of biodiesel. Differences in fuel energy content between different sources of pure biodiesel are shown in Table 2 (United States Environmental Protection Agency, 2002).

Table 2 Average Energy Content of 100% biodiesel

Fuel Base	Average net Btu/gal
All biodiesels	118.296
Animal	115.720
Rapeseed/canola	119.208
Soybean	119.224
Rapeseed or Soybean	119.216

Industry experts recommend that biodiesel be used within six months of production to ensure that the quality of the fuel is maintained. Fuel degradation for biodiesel is more likely with higher concentration blends due to the higher presence of the biodiesel, so stability concerns and issues (fuel system deposits, clogged filters, etc.) are likely to be higher and may occur faster as the blend level is increased. There have been very few field reports of stability related problems with B20 and lower blends in the US when the biodiesel meets D6751 prior to blending and the fuel is used within six months.

2.2.1.2 Biodiesel Emissions

Based on the energy and carbon content of the fuels, biodiesel blends may actually increase emissions of carbon dioxide relative to conventional diesel fuel. This potential increase is small and it is unlikely to be discernable given the variability in the composition of each fuel. EPA test results suggest that there are no measurable differences between the tailpipe carbon dioxide emissions of biodiesel and standard diesel (United States Environmental Protection

Agency, 2002). The carbon dioxide benefits commonly attributed to biodiesel are the result of the renewability of the biodiesel itself, not the comparative exhaust emissions (United States Environmental Protection Agency, 2002).

Vehicles running biodiesel blends have slightly elevated nitrous oxide emissions but the use of a cetane improving additive may offset these losses (Edwards, et al., 2005). For biodiesel blends that are otherwise identical, increasing the cetane number from 40 to 47 could produce a nitrous oxide reduction of 3% versus standard diesel (Proc, et al., 2006) . The nitrous oxide emission of biodiesel blends also varies depending on the feedstock used to produce the biodiesel and the type of conventional diesel to which the biodiesel is added (United States Environmental Protection Agency, 2002). Biodiesel based on animal fat, for example, naturally has a higher cetane number than plant based biodiesel and also has nitrous oxide emissions equivalent to conventional diesel (Wyatt, Aug 2005). The results of several studies on the impact of various biodiesel blends on the tailpipe emissions of heavy-duty diesel vehicles are shown in Table 3. It is important to note that these reductions are on an equivalent mile basis.

Table 3 Expected Change in Tailpipe Emissions for Biodiesel versus Standard Diesel

Biodiesel Blend	Percent Change in Tailpipe Emissions						
	Sulfur Oxides	Nitrogen Oxides	Total Hydrocarbons	Carbon Monoxide	Carbon Dioxide	Particulate Matter	Source
B20	-20%	2%	-10%	-10%	-	-15%	(National Biodiesel Board)
	-20%	2%	-20%	NA	NA	-10%	(Edwards, et al., 2005)
	NA	2%	-20%	-12%	NA	-12%	(Koyama, 2005)
	NA	-4%	-28%	-24%	NA	-20%	(Proc, et. al 2006)
B100	-100%	9%	-40%	-50%	-	-70%	(National Biodiesel Board)
	NA	10%	-67%	-47%	NA	-48%	(Koyama, 2005)

2.2.1.3 Biodiesel Production

Biodiesel can be produced from a variety of renewable sources including soybean oil, corn oil, canola oil, cottonseed oil, recycled restaurant oils, tallow, lard, grease recovered from restaurants, and float grease from waste water treatment plants. The most common feedstock in the US is soybean oil and most biodiesel in Europe is made from rapeseed oil (Fortenbery, 2005). The production of biodiesel requires several steps. First, raw oil must be extracted from the feedstock. Once obtained, the raw oil is filtered, collected in a tank, and then periodically pumped into an agitating transesterification reactor. Transesterification is the process of exchanging the alkoxy group of an ester compound by another alcohol, essentially changing an alcohol and an ester into a different alcohol and ester. Methanol is the most cost effective alcohol to use in this reaction. After transesterification, the product is transferred to the finishing reactor where various chemicals and processes are used to neutralize or remove fats, soaps, and solids. The result is a liquid fuel similar to diesel fuel derived from crude oil (Delucchi, 2006). Current technology is estimated to yield about 3.2 units of energy for every unit of energy consumed in the production process (Fortenbery, 2005).

Transport and delivery of biodiesel requires no significant changes to existing infrastructure, as it can be handled in a manner similar to petroleum diesel. It is relatively easy to manufacture biodiesel blends because biodiesel and petroleum diesels can be splash blended and stored in the same tank (Fortenbery, 2005).

2.2.1.4 Biodiesel Lifecycle GHG Emissions

Much of the carbon contained in biodiesel was originally removed from the atmosphere by plants which would imply that there is little net increase in atmospheric carbon dioxide levels as a result of biodiesel use.   All biologically derived fuels do, however, have GHG emissions associated with the production process which include: cultivation and harvest of the biological feedstock, transport of the feedstock to the conversion facility, conversion of the feedstock to a finished fuel, distribution of the finished fuel to stations, dispensing of the fuel, and use of the fuel in vehicles (Delucchi, 2006). Research by the National Renewable Energy Laboratory reports a 79% reduction in net CO_2 emissions from biodiesel relative to petroleum diesel (Fortenbery, 2005). Edwards et al. estimates a reduction in GHG emissions of 63% for plant based biodiesel and 93.5% for animal based biodiesel (Edwards, et al., 2005). Due to discrepancies in the methods some analysts believe that plant-based biodiesel has higher lifecycle GHG emissions than conventional diesel because of the large N_2O emissions from agriculture and the large emissions of carbon due to changes in land use (Delucchi, 2006). Emissions of N_2O from nitrogen fixation by soybeans, for example, may be on a par with CO_2 emissions from fuel combustion (Delucchi, 2006).

Biodiesel made from a waste product also have lower lifecycle GHG emissions than the same fuel made with a product that has to be purchased. This comes about because the rules associated with life cycle analysis which specifies that in such situations the upstream emissions in generating the waste product do not have to be debited to the final product. Biodiesel made with waste cooking oil is the best form of biodiesel on a life-cycle basis (Beer, et al., 2001).

2.2.1.5 Biodiesel Safety

Biodiesel is nontoxic. The acute oral lethal dose is greater than 17.4 grams per kilogram of body weight. By comparison, table salt is nearly 10 times more toxic. Within 28 days, pure biodiesel degrades 85 to 88 percent in water, which is four times faster than standard diesel.

Blending biodiesel with diesel fuel accelerates biodegradability of standard diesel. For example, blends of 20% biodiesel and 80% diesel fuel degrade twice as fast as standard diesel alone. Biodiesel's flash point is over 200° Fahrenheit, well above petroleum based diesel fuel's flash point of around 125° Fahrenheit. Testing has shown the flash point of biodiesel blends increases as the percentage of biodiesel increases. Therefore, biodiesel and blends of biodiesel with petroleum diesel are safer to store, handle, and use than standard diesel (National Biodiesel Board).

2.2.1.6 Biodiesel Social benefits

Biodiesel is produced from derivatives of a biological system, which allows for renewable seasonal production (Fortenbery, 2005). Biodiesel can enhance our energy security because it can be manufactured using existing industrial production capacity and domestic surpluses of vegetable oils. The maximum capacity of US biodiesel production is estimated to be 4.64 billion gallons per year, which constitutes about 15% of total US annual diesel demand. While there may not be a large substitution away from petroleum based diesel as the result of a more fully developed domestic biodiesel industry, domestic biodiesel production could have a positive influence on both domestic prices and price volatility (Fortenbery, 2005).

2.2.1.7Biodiesel Vehicle Performance

Biodiesel offers several fuel advantages over petroleum diesel, including improved lubricity, a higher flash point, lower toxicity, and biodegradability (Wyatt, Aug 2005) and on average, the natural cetane number of biodiesel is higher than that for conventional diesel fuel (United States Environmental Protection Agency, 2002). Cetane number is a measurement of the combustion quality of diesel fuel during compression and represents the time period between the start of injection and start of combustion of the fuel. Higher cetane fuels will have shorter ignition delay periods

A potential disadvantage of biodiesel is the poor cold start performance relative to standard diesel, but this is more of an issue for B100 than B20 fuels. B100 will begin to freeze at temperatures around 25°F and animal fat-based biodiesels generally have even poorer cold-temperature properties (Wyatt, Aug 2005). Vehicle owners can solve cold start problems with biodiesel in the same manner as with conventionally fueled vehicles by using engine block heaters, fuel filter heaters or storing the vehicles near or in a building.

Blends higher than B20 may cause a larger amount of unburned fuel to make its way past the piston rings and into the oil pan. This is due to the slightly higher viscosity and the slightly higher density of biodiesel. High levels of biodiesel present in the engine oil may polymerize over time and cause serious engine oil sludge problems. Engine oil change intervals may need to be shortened significantly if using high blends of biodiesel. The viscosity and density of B20 and lower blends are very similar to that of the pure petrodiesel, and this phenomenon has not been problematic with blends of B20 or lower so no changes in engine oil intervals are needed with B20 or lower. Most engine manufacturers have provided positive statements about the use of B20 in their heavy duty engines. However, a few, such as Volkswagen, limit biodiesel use to a 5 percent blend or less until they receive greater assurance of fuel quality, material compatibility, and fuel stability (Koyama, 2005).

B100, on average, has 7-9% lower energy content than average than standard diesel on a volumetric basis. On average, B20 will decrease energy content of standard diesel by 1-2%. While BTU changes of 1-2% can be picked up in lab tests for horsepower, torque, and fuel economy, normal variability in the field make it very difficult to detect any impact with B20 and lower blends for these parameters. Some fleets have even shown fuel economy increases with

B20, although this is unexpected based on the energy content of the fuel. With blends higher than B20, the impact on power or fuel economy may be great enough to become noticeable by the user and the penalty in fuel economy may offset any fuel cost reduction (United States Environmental Protection Agency, 2002). Chassis dynamometer test of heavy-duty diesel vehicles running B20 indicated between a 2.1% and 2.4% reduction in fuel economy (Proc, et al., 2006).

2.2.1.8 Biodiesel Fuel Costs

Biodiesel blends are compatible with the existing infrastructure for petroleum diesel and capable of being stored in the same fuel tanks and tanker trucks. Assuming that a mature distribution system is in place, approximately 75% of the final biodiesel product cost would be due to the cost of feedstock oil. The remaining 25% is attributable to processing, handling, capital recovery, plus a small profit margin (Wyatt, Aug 2005). Because feedstock cost dominates the production economics, larger volume production will not greatly affect final product costs for soy-based biodiesel. The US 2007 national average for B20 and B100 is $2.96 per gallon and $3.31 per gallon respectively, which corresponds to a cost of $3.02 and $3.59 per diesel-equivalent gallon (United States Department of Energy, 2007). This represents an increase of 2% and 19% over the cost of diesel in the same time period.

2.2.1.9 Biodiesel Summary

Although biodiesel costs more than standard diesel, fleet managers can make the switch to alternative fuels without purchasing new vehicles, acquiring new spare parts inventories, rebuilding refueling stations, or hiring new mechanics. In addition, buying biodiesel in bulk quantities decreases the fuel's cost. Biodiesel is a renewable bio-based fuel and, depending on the source of the feedstock, may have lower lifecycle GHG emissions versus diesel derived from mineral oils. Neat biodiesel contains almost no sulfur and no aromatics and is expected to lower particulate exhaust emissions. Biodiesel is also bio-degradable and non-toxic (Beer, et al., 2001).

Due to the high oxygen content of biodiesel, it produces relatively high NOx levels during combustion and the oxidation stability is lower than diesel which lowers storage life. Biodiesel is also hygroscopic, so contact with humid air must be avoided. The lower volumetric energy density of biodiesel means that more fuel needs to be transported for the same distance traveled. Biodiesel can also cause dilution of engine lubricant oil, requiring more frequent oil changes engines (Beer, et al., 2001).

2.2.2 Natural Gas

Natural gas is between 95–99% methane with a small percentage of ethane, propane and heavier hydrocarbons. There are also trace amounts of nitrogen, carbon dioxide and oxygen. Impurities can include water vapor, hydrogen sulfide, and entrained particulates (New York State Energy Research and Development Authority, 1997). The actual composition of the gas is dependent on the source and the refining process. Natural gas has a very low energy density at standard temperature and pressure when compared to diesel, which means the gas must be compressed or liquefied to achieve sufficient vehicle range. Compressed natural gas is referred to as CNG and liquefied natural gas is referred to as LNG. Each storage method will result in different fuel cost, vehicle cost, and vehicle range. Since LNG must be vaporized before entering the combustion chamber, both storage methods will result in approximately the same vehicle performance and tailpipe emissions. Information should be considered to apply for both LNG and CNG unless otherwise noted.

2.2.2.1 CNG Storage Technology

Even if natural gas is compressed to 3600 psi, the fuel system needs at least 3.35 times the fuel storage volume to produce a vehicle range equivalent to a diesel vehicle. CNG cylinders are also constrained to spherical or cylindrical shapes to withstand the large internal pressure which makes tanks difficult to mount in traditional locations (EA Engineering, Science, and Technolgy, Inc., 1997). Since the fuel tanks are typically located on the sides of the vehicles in the target application, drivers may have a difficult time maneuvering the vehicle if the outer dimensions are increased. This implies that space for extra fuel storage is limited. Since the volume of fuel is constrained, the low energy density of natural gas results is a drastically reduced vehicle range. Reduced vehicle operating range is the greatest physical drawback for CNG. It is also important to recognize that CNG cylinders weigh significantly more than the tanks used for petroleum fuels. Reinforced aluminum cylinders weigh approximately 25 pounds per diesel equivalent gallon of natural gas (EA Engineering, Science, and Technolgy, Inc., 1997).

2.2.2.2 LNG Storage Technology

Liquefied natural gas is methane which has been purified and condensed to liquid form by cooling cryogenically to -260°F (-162°C). At atmospheric pressure, it occupies only 1/600 the volume of natural gas vapor (Chandler, et al., 2004). Because it must be kept at such cold temperatures, LNG is stored in double-wall, vacuum-insulated pressure vessels. A gallon of LNG has about 60% of the energy content of a gallon of diesel fuel. Assuming equal energy storage, LNG fuel systems take up about half the volume of CNG systems and the weight of the system is reduced by half. Compared to diesel tanks, however, LNG tanks are larger, heavier, and more expensive (Chandler, et al., 2004). LNG is generally considered to makes the use of natural gas practical for heavy-duty vehicles that travel long distances (EA Engineering, Science, and Technolgy, Inc., 1997).

2.2.2.3 Natural Gas Technology

The high autoignition temperature and low cetane rating indicates that natural gas is a poor diesel engine fuel, but a high octane rating and knock resistance make it well suited for a spark ignited otto-cycle engines (EA Engineering, Science, and Technolgy, Inc., 1997). Natural gas can be combusted in a number of ways including stoichiometric, lean-burn and dual-fuel diesel. Stoichiometric combustion is spark ignited with equal parts fuel and air while learn burn is also spark ignited but uses more air than necessary. Dual-fuel diesel combustion is also lean burn but uses a small amount of diesel in addition to natural gas to allow for compression ignition (M.J. Bradley & Associates, Inc., February 2000).

The simplicity of the fuel molecule is advantageous for soot-free complete combustion, but poses an additional problem of excessive methane emissions (Nils-Olof Nylund, 2000). As methane is a non-reactive hydrocarbon, tailpipe emissions of methane are not as well controlled by conventional catalytic converters (Beer, et al., 2001). There are two basic ways to control emissions from natural gas engines. One method is to use a three-way catalyst in a stoichiometric engine equipped with a closed-loop fuel system. The three way catalyst gives very low emissions and is used for most current light-duty and also some heavy duty applications. The second method is to use lean-burn combustion because the formation of nitrous oxides is controlled in the combustion process itself (Nils-Olof Nylund, 2000). Due to the expense of three-way catalysts, most of the CNG buses offered today in the United States have lean burn engines to minimize NO_x emissions without the need for a NO_x after treatment device (M.J. Bradley & Associates, Inc., February 2000).

The ISXG engine, developed by Cummins Westport, is an example of a dual-fuel strategy utilizing LNG and diesel. In this system, LNG is pumped up to high pressure, vaporized, and delivered to the engine at approximately 3,000 psi along with a small amount of high-pressure diesel. The diesel and natural gas are injected simultaneously into each cylinder through a single fuel injector, which fits in the same space as a diesel fuel injector. The diesel provides ignition for the natural gas in the compression ignition cycle. Currently, between 6% and 7% of the energy content used by the prototype ISXG engine is from diesel. The engine cannot operate on diesel alone unless the Westport-Cycle HPDI natural gas fuel system and injectors are removed and replaced with standard diesel equipment (Chandler, et al., 2004).

2.2.2.4 Natural Gas Emissions

Methane is less reactive in the atmosphere, which means that any natural gas which is not burned in the combustion process does not participate significantly in the reactions that form ozone. CNG vehicles also have the advantage of not having evaporative, running loss, or refueling emissions due to their closed fuel systems. Total hydrocarbons, however, are higher when using natural gas since methane is difficult to oxidize in catalytic converters. Natural gas engines require less fuel enrichment for cold-start and acceleration because the fuel is fully vaporized when it enters the engine and less fuel enchainment leads to lower carbon monoxide emissions (New York State Energy Research and Development Authority, 1997). Vehicles using natural gas also have an inherent advantage in CO emissions because natural gas contains more hydrogen and less carbon (New York State Energy Research and Development Authority, 1997).

Natural gas burns with little or no particulate emissions and it can be burned lean enough to have low nitrous oxide emissions. Any particulate emissions from a CNG engine are most likely generated from engine lubricating oil and not the fuel (New York State Energy Research and Development Authority, 1997). The primary trade-off for these lower emissions is reduced engine efficiency primarily due to the conversion to spark ignition (EA Engineering, Science, and Technolgy, Inc., 1997). The decisive factors for total reduction in regulated emissions for a CNG engine the exhaust gas after treatment technology used on the vehicle and the ignition strategy (Nils-Olof Nylund, 2000).

Viking Freight, in conjunction with the National Renewable Energy Laboratory, Cummins Westport, and West Virginia University, tested the emissions from two diesel and two natural gas tractor-trailers under the EPA standard Urban Dynamometer Driving Schedule (UDDS) and a custom Viking drive cycle. The results of this study are shown in Table 6 along with the results of several other studies investigating the effect of CNG in heavy-duty diesel vehicles.

Table 4 Expected Change in Tailpipe Emissions for CNG versus Standard Diesel

Fuel	Percent Change in Tailpipe Emissions						
	Sulfur Oxides	Nitrogen Oxides	NMHC	Carbon Monoxide	Carbon Dioxide	Particulate Matter	Source
Natural Gas	NA	-35%	-20%	-90%	-6%	-90%	(Lyford-Pike, 2003)
	NA	-27%	-66%	-84%	-3%	-95%	(New York State Energy Research and Development Authority, 1997).
	-90%	-35%	NA	NA	-11%	-95%	(Edwards, et al., 2005)
	NA	-55%	NA	NA	NA	-85%	(M.J. Bradley & Associates, Inc., February 2000).

2.2.2.5 Natural Gas Production

Most natural gas consumed in the United States is domestically produced, with significant importation from Canada and a small but rapidly growing contribution from overseas imports of LNG. The majority of natural gas is considered fossil fuel, but other supplemental sources include synthetic gas and coal-derived gas. There are also renewable sources of natural gas, such as biomethane, which is a pipeline-quality natural gas-substitute produced by purifying biogas obtained from landfills, animal waste “lagoons,” and sewage processing plants.

Gas trapped in sub-surface porous rock reservoirs is extracted via drilling. Gas streams produced from oil and gas reservoirs contain natural gas, liquids, and other materials. Processing is required to separate the gas from petroleum liquids and to remove contaminants. The gas is separated from free liquids such as crude oil, hydrocarbon condensate, water, and entrained solids.

The United States has a vast natural gas distribution system, which can quickly and economically distribute natural gas to and from almost any location in the contiguous 48 states. Gas is distributed between and within states by 300,000 miles of transmission pipelines and an additional 1.9 million miles of distribution pipes transport gas within utility service areas. The distribution system also includes thousands of delivery, receipt, and interconnection points; hundreds of storage facilities; and more than 50 points for exporting and importing natural gas.

Most natural gas fueling stations dispense compressed natural gas (CNG), which is either compressed on site or compressed off site and transported to the station in tanks. The availability of liquefied natural gas stations is more limited. Most LNG users are fleets that have LNG infrastructure dedicated to their vehicles. Only a few large-scale liquefaction facilities provide LNG fuel for transportation nationwide. While liquefying natural gas can be done on site, costs and operational complexity of LNG plants of this size would equal or exceed those of compressor-based stations (EA Engineering, Science, and Technolgy, Inc., 1997). An alternative option for a LNG refueling stations is to have tanker trucks deliver LNG once a day. In most areas, a single tanker truck can deliver 11,000 gallons of LNG which is the equivalent of 6,000 to 7,000 gallons of diesel fuel (EA Engineering, Science, and Technolgy, Inc., 1997).

Onshore production of unconventional natural gas is expected to be a major contributor to growth in U.S. supply, increasing from 8.5 trillion cubic feet in 2006 to 9.5 trillion cubic feet in 2030 (Energy Information Administration, 2008). Most of the increase in unconventional production is projected to come from shale gas, which is natural gas trapped in fine grain shale deposits. The Alaska natural gas pipeline is expected to be completed in 2020, and after the pipeline goes into operation, Alaska's total natural gas production will increase from 0.4 trillion cubic feet in 2006 to 2.4 trillion cubic feet in 2030 (Energy Information Administration, 2008).

Degradable organic matter can be a renewable source of non-fossil fuel based methane. One of the most intriguing and promising sources of biogas methane is landfill gas. This gas contains methane, carbon dioxide, and other substances, some of which are toxic. Processes exist to strip carbon dioxide and other impurities from the methane stream, and are similar in nature to the LNG process (Edwards and Kelcey, 2005). A study conducted by the Franklin County Landfill in Ohio indicated that they could supported the daily demand of 20 LNG refuse haulers, and indicated a total potential of 22,080 gallons per day (Edwards and Kelcey, 2005).

2.2.2.6 Natural Gas Lifecycle GHG Emissions

Natural gas can contain significant quantities of naturally occurring CO_2, which in the past has often been vented to the atmosphere at the well-head. Vented CO_2 accounts for between 3 and 15 % of full fuel-cycle CO_2 emissions from NG combustion (Beer, et al., 2001). Methane leakage from containers and fuel systems, referred to as fugitive losses, also contributes significantly to the lifecycle GHG emissions. Quantification of fugitive losses from methane distribution depends on the scenario adopted for transport. On-site liquefaction and transport via truck results in negligible fugitive losses but pipeline distribution of NG introduces much greater fugitive emissions (Beer, et al., 2001). The GHG emissions of LNG are estimated to be between 13 and 19% percent less than diesel and CNG is estimated to be around 6% less than diesel.

2.2.2.7 Natural Gas Safety

On release to the atmosphere, CNG is much lighter than air and thus it is safer than spilled diesel. In the case of a CNG leak, because of the gaseous nature of the fuel, the gas will issue as a very high velocity jet into the surroundings which aides in the rapid dispersion of the fuel. (Beer, et al., 2001). Compared to conventional fuels, LNG's flammability is limited. It is nontoxic, odorless, noncorrosive, and noncarcinogenic. It presents no threat to soil, surface water, or groundwater (Chandler, et al., 2004). The fuel storage cylinders used in NGVs are much stronger than petrol tanks. The design of NGV cylinders are subjected to a number of specified "severe abuse" tests, such as heat and pressure extremes, gunfire, collisions and fires. Though fuel storage cylinders are stronger than petrol tanks, when composite material used to encase the tanks, the materials are fundamentally more susceptible to physical damage than metals under abusive conditions (Beer, et al., 2001).

2.2.2.8 Natural Gas Social Benefits

Natural gas is an abundant domestic fuel and also can be derived from renewable sources. The U.S. Department of Energy supports natural gas vehicle research and development to help the United States reach its goal of reducing dependence on imported petroleum (Beer, et al., 2001). LNG is less beneficial to energy security because it is used primarily for international trade in natural gas and for meeting seasonal demands for natural gas. It is produced mainly at LNG storage locations operated by natural gas suppliers, and at cryogenic extraction plants in gas-producing states. Only a handful of large-scale liquefaction facilities in the United States provide LNG fuel for transportation (Chandler, et al., 2004).

2.2.2.9 Natural Gas Vehicle Performance

Natural gas has a high octane rating (~130) and therefore a low cetane rating. It is therefore best suited to spark ignited engines rather than compression ignited engines. Since most medium and heavy-duty engines are compression ignition engines, for natural gas applications they are converted to spark ignition engines. This conversion involves reduction in the compression ratio and there is usually a drop in the efficiency of the engine (Edwards, et al., 2005). The trade-off from going to spark ignition operation is that vehicle fuel economy is reduced by 10% to 25%. The reductions are highest at idle because diesel engines can operate without a throttle because of in-cylinder fuel injection and stratified charge combustion. This fact greatly lowers pumping losses relative to spark ignited engines which must use a throttle and don't have stratified charge combustion (EA Engineering, Science, and Technolgy, Inc., 1997). At high engine loads and speeds, the efficiency difference between the two types of engines is small (New York State Energy Research and Development Authority, 1997). Engines using a small amount of diesel to ignite the CNG provide diesel-like power and efficiency, but are still in early stages of development. The energy equivalent fuel economy was only 10.5% lower than diesel for a prototype LNG truck operating with the dual fuel approach (Chandler, et al., 2004).

Viking Freight reported the fuel economy of the diesel trucks was approximately 6.1 mpg over the UDDS and 7.9 mpg over the Viking drive cycle. The fuel economy of the spark ignition natural gas trucks was approximately 4.8 mpeg over the UDDS and 6.3 mpeg over the Viking cycle, which represents an average energy based fuel economy penalty of 21% and 20%, respectively (Lyford-Pike, 2003). In a test performed by the National Renewable Energy Laboratory (NREL), average fuel economy was 5.17 mpeg for the natural gas trucks and 6.73 mpg for the diesel trucks. This represents a 23.2% fuel economy penalty for the natural gas trucks (Lyford-Pike, 2003). Newer CNG engine, such as the Cummins Westport ISL-G, which utilizes lean burn technology and exhaust gas recycling, are likely to be more efficient and already meet US EPA and California Air Resources Board (CARB) 2010 emissions standards (Cummins Westport). It is expected that standard diesel engines will need to sacrifice fuel efficiency to meet these standards.

2.2.2.10 Natural Gas Costs

Natural gas vehicles are more costly due to low production volumes and relatively expensive on-board fuel storage system. However, the California Energy Commission and the California Air Resources Board have postulated that future diesel engines may cost more due to the added cost of advanced emission control technologies required to meet 2010 Federal and California emission standards and resultant impact on fuel economy (Schubert, et al., July 2005). The incremental cost of a natural gas Westport HPDI equipped truck compared to a diesel truck is estimated to be approiximately $30,000 in 2007 and predicted to decline with growth in production to near zero by 2010 (Edwards, et al., 2005).

High annual mileage combined with the low price per-gallon of CNG can create sufficient fuel cost savings to enable vehicle owners to recover their investment in a reasonable amount of time (New York State Energy Research and Development Authority, 1997). The price of commercial CNG price was $2.34 per diesel-equivalent gallon, or $18.18 per MMBTU, in 2007. This represents a reduction of 21% versus the cost of standard diesel (United States

Department of Energy, 2007). There also may be potential saving in purchasing natural gas though utility companies and processing it onsite. The cost of natural gas though utility companies is usually correlated to the Henry Hub natural gas spot price, which average averaged $7.17 per thousand cubic feet (Mcf) in 2007 and is expected to average $7.83 per Mcf in 2008 and $7.93 per Mcf in 2009 (Energy Information Administration, February 2008).

2.2.2.11 Natural Gas Summary

CNG has very low particulate emissions because of its low carbon to hydrogen ratio and there are negligible evaporative emissions. The low carbon to hydrogen ratio also means it produces less carbon dioxide per GJ of fuel compared to diesel. A lower adiabatic flame temperature compared to diesel, also leads to lower NOx emissions. Engines fuelled with natural gas in heavy-duty vehicles offer quieter operation than equivalent diesel engines, making them more attractive for use in urban areas. Natural gas also has nearly zero sulfur levels which mean the engine releases negligible sulfate emissions.

The most significant drawback for CNG is reduced driving range. Fuel cost is low, but vehicle capital costs are high, indicating that economics are best with vehicles that are used intensively. The high cost of refueling equipment also discourages establishment of CNG and LNG refueling stations. Only a vehicle that uses large quantities of fuel, either because the vehicle has low fuel economy, high annual mileage, or both, is a good candidate for natural gas if the vehicle owner is trying to accomplish a three-year simple payback (New York State Energy Research and Development Authority, 1997). Natural gas engines have higher levels of methane tailpipe emissions, which are a greenhouse gas, compared with diesel and fugitive emissions of methane can have a significant effect on the lifecycle greenhouse gas emissions. (Beer, et al., 2001).

2.2.3 Ethanol

Ethanol is a flammable, colorless chemical compound also known as ethyl alcohol, drinking alcohol or grain alcohol. It is a straight-chain alcohol and its molecular formula is variously represented as EtOH, CH_3CH_2OH, C_2H_5OH or as its empirical formula C_2H_6O. Nearly one-third of U.S. gasoline contains ethanol in a low-level blend to oxygenate the fuel or reduce air pollution. Ethanol is also widely available in E85, a high-level blend that can be used in flexible fuel vehicles. Ethanol may also be blended with additives into diesel fuels for applications in which oxygenation may improve diesel engine emission performance (Wang, 2003). This ethanol-diesel blend, or E-diesel, is the most practical approach for ethanol use in heavy- duty diesel vehicles.

2.2.3.1 Ethanol Technology

E-diesel is a blend of standard diesel containing up to 15% anhydrous ethanol and a specially designed additive package for blend stability and to achieve certain fuel properties (Wang, 2003). There are two additive-based approaches to maintaining stable E-Diesel blends at low temperature: adding emulsifiers to produce stable micro emulsions or adding co solvents to produce stable solutions. Currently there are five predominant blend additive vendors: Pure Energy Corporation, O2 Diesel (formerly AAE Technologies), AKSO Nobel, Lubrizol, and GE Betz (formerly Betz-Dearborn). The first four of these state that their additive package is co solvent-based, while the Betz-Dearborn additive is an emulsifier.

The amount of additives varies between 0.5% and 5% of the blend by volume (Löfvenberg, 2002). Adding ethanol lowers the cetane number of the mixture, so the additive package often includes a cetane improver. An additional component of the additive package provides corrosion protection and improves lubricity. The ratio of the components can easily be changed to tailor the properties of the E-Diesel mixture (Löfvenberg, 2002). For E-Diesel blends ranging from 7.5% to 15%, the treat rate of additives ranges from about 1% to 1.5% by volume (Wang, 2003).

2.2.3.2 Ethanol Emissions

E-diesel blends are expected to reduce particulate matter emissions and carbon monoxide emissions. Various evaluators have reported 20 to 40% PM reductions and 20 to 30% CO reductions. The effects of E-Diesel on nitrous oxide emissions have been generally insignificant (Waterland, et al., 2003). Use of E-diesel blends relative to use of petroleum diesel results in few changes in carbon dioxide emissions, primarily because E-diesel blends offer heating value-based fuel economy which is lower than that of petroleum diesel (Wang, 2003). Although many researchers have reported small nitrous oxide reductions, it should be recognized that some rpm and load combinations actually increased the emission rate (Wang, 2003). The emission of volatile organic compounds is also expected to increase slightly with the use of E-Diesel.

An E-diesel demonstration in Denmark used a Scania heavy duty tanker truck running an E-diesel mixture of 88%, 10% ethanol, and 2% Beraid® additive (Löfvenberg, 2002). The emissions were tested using European 5-mode test for diesel engines. The result of this study is shown in Table 5 along with the results of several other studies.

Table 5 Expected Change in Tailpipe Emissions for E-diesel versus Diesel

Fuel	Percent Change in Tailpipe Emissions						
	Sulfur Oxides	Nitrogen Oxides	NMHC	Carbon Monoxide	Carbon Dioxide	Particulate Matter	Source
ED7	-5%	same	0%	NA	NA	-25%	(Edwards, et al., 2005)
ED10	NA	same	NA	NA	NA	-20%	(Wang, 2003)
	NA	same	5%	5%	NA	-20%	(Wang, 2003)
	NA	-5%	NA	-29%	NA	-31%	(Löfvenberg, 2002).
ED15	NA	2%	8%	8%	NA	-25%	(Wang, 2003)

2.2.3.3 Ethanol Production

To produce ethanol from corn, the starch portion of the grain is exposed and mixed with water to form a mash. The mash is heated and enzymes are added to convert the starch into glucose. Yeast is added to ferment the glucose to ethanol, water, and carbon dioxide. This fermentation product, called "beer," is boiled in a distillation column to separate the water, resulting in ethanol (Delucchi, 2006). A cellulose-to-ethanol process differs from the grain-to-ethanol processes in that the cellulosic process uses parts of the original biomass feedstock which cannot be fermented, such as lignin, for process heat while the grain method utilizes fossil fuels (Delucchi, 2006). The cellulose-to-ethanol process is estimated to produce 1.5 units of energy for each unit of energy consumed in the manufacturing process (Fortenbery, 2005).

Ethanol can be produced in two forms; hydrated and anhydrous. Hydrated ethanol has a purity of 95% suitable for blending with an ignition improver, or as a 15% emulsion in diesel that is known as E-diesel. A second stage refining process is required to produce anhydrous ethanol, which is 100% pure, for use in ethanol blends in gasoline (Beer, et al., 2001). Many fuel distributors in the U.S. currently splash blend ethanol into gasoline by pouring the two components directly into tanker trucks for delivery to customers marketing gasoline E10 (Waterland, et al., 2003). The solubilizer additive enables anhydrous ethanol and diesel oil to be splash blended, even at low temperatures (Wang, 2003).

2.2.3.4 Ethanol Lifecycle Carbon GHG Emissions

The lifecycle analysis for ethanol is similar to biodiesel in that tailpipe carbon emissions are not considered GHG because they are biologically derived. Corn ethanol has approximately the same GHG emissions as gasoline, which is slightly higher than diesel. Cellulosic ethanol, however, has 50% less GHG emission compared to gasoline. The main reason for this difference is the relatively high emissions from fertilizer production, land use, cultivation, and from emissions of non-carbon GHGs from vehicles (Delucchi, 2006). For a blend of 7.7% ethanol and diesel the lifecycle GHG emissions are expected to decrease by 2.8% compared to standard diesel (Edwards, et al., 2005).

2.2.3.5 Ethanol Safety

The major concern with E-diesel as an alternative fuel for heavy-duty vehicles is the increased safety risk posed by fire or explosion (Waterland, et al., 2003). This is primarily because the flash point and flammability characteristics of E-diesel are those of alcohol (Beer, et al., 2001). Engine manufacturers will usually not warranty their engines for use with E-diesel because of concerns about safety, liability, and component materials compatibility (Edwards, et al., 2005). More testing of E-diesel will be necessary to alleviate this issue. To prevent fuel-ethanol from being consumed by humans, it is typically denatured by adding five-volume-percent gasoline before it leaves the production plant although other denaturants are approved for use (New York State Energy Research and Development Authority, 1997).

2.2.3.6 Ethanol Social Benefits

Ethanol has the same social benefits as biodiesel and other biologically derived fuels. The increased use of ethanol is also expected to help reduce the need for agricultural subsidies. There is controversy, however, over increased price of corn and other feed stocks due to increased demand for ethanol.

2.2.3.7 Ethanol Vehicle Performance

Ethanol contains less energy per gallon than diesel (New York State Energy Research and Development Authority, 1997). The drivers in the E-diesel demonstration in Denmark commented that they could feel a reduction in maximum engine power and found it necessary to shift gears more often. The drop in engine power was estimated to be approximately 10% by the drivers. A chassis dynamometer test shows a reduction in engine power for e-diesel between 5 and 8% (Löfvenberg, 2002). A standard heavy-duty diesel engine can run on E-diesel without being modified and there was no sign of wear and tear (Löfvenberg, 2002). In heavy-duty truck tests conducted by the Southwest Research Institute, two 1999 model year Mack E-7 units were tested running ED10 and ED15. The trucks experienced a net 7% and 10% loss in fuel economy, relative to diesel fuel, while running ED10 and ED15 respectively (Wang, 2003).

2.2.3.8 Ethanol Fuel Costs

Ethanol is currently made by fermenting sugars from corn and other agricultural feedstock. Ethanol made via fermentation is expensive and debate continues about whether the energy used to produce crops and then convert them to ethanol is greater than the energy content of the ethanol fuel. On the plus side, much of the energy used to produce ethanol is derived from natural gas, propane, and coal, which are all largely domestic resources. Thus, even if the energy balance is questionable, the net result of ethanol use in vehicles would be a reduction in both imported energy and dependence on petroleum fuels (New York State Energy Research and Development Authority, 1997). Ethanol costs more than diesel fuel on an energy equivalent basis, which results in a higher cost for the blended fuel. E-diesel blends also require an additive to keep the two components in suspension. The costs of these additives are guarded by the manufacturers but they add at least one to two cents to the blend cost depending in part on the quantity of additive required (Edwards, et al., 2005). E-diesel is not commercially available at this time, so data on the average price for 2007 is not available. The price of E-85 averaged $2.63 per gallon in 2007 and the price of diesel averaged $2.96 per gallon (United States Department of Energy, 2007). If the cost of pure ethanol is approximated as the cost of E-85, an ED-15 blend would cost approximately $2.91 per gallon. The volumetric energy content of the blend is lower, however, so this price would approximately be $3.16 per diesel-equivalent gallon which represents an increase of 7% compared to standard diesel.

2.2.3.9 Ethanol Summary

E-diesel fairs poorly when evaluated in terms of the cost effectiveness of reducing impact weighted emissions. Elevated nitrous oxide emissions may offset the benefit of reducing carbon monoxide and particulate matter (Edwards, et al., 2005). An E-Diesel task force has been established under the auspices of the Renewable Fuels Association to begin the process of registering E-Diesel with the EPA. This process will likely take several years to complete and the full commercialization of the fuel in the US will not be possible until the process is complete (Edwards, et al., 2005).

2.2.4 Methanol

Methanol, like ethanol, is clear liquid alcohol with low volatility and faint odors. Unlike gasoline and diesel, which contain a wide assortment of hydrocarbon molecule types, methanol is a single molecule liquid (New York State Energy Research and Development Authority, 1997). The chemical structure of methanol is CH_3OH. Methanol is usually derived from natural gas, but can also be derived from coal or biomass. As a fuel, methanol is most often used as a blend called M85, which is a blend of 85% methanol and 15% gasoline by volume. It can also be used in an almost pure form called M100 (Yacobucci, 2005).

2.2.4.1 Methanol Technology

Methanol's cetane rating is between 0 and 10, while diesel fuel has cetane ratings in the range of 40 to 55. Diesel engines must either incorporate special features to overcome the low cetane of methanol or additives can be used to increase the cetane rating to levels similar to diesel fuel. Each approach has its advantages and disadvantages, but the emissions benefits of methanol are the same in either case. Methanol has less lubricity than diesel fuel, which causes problems with some fuel injection equipment but lubricity additives are available to mitigate this disadvantage (EA Engineering, Science, and Technolgy, Inc., 1997).

Regardless of the approach taken, the vehicle's fuel tanks and other fuel system components can be simple variations of diesel-fuel components. Detroit Diesel Corporation developed the only methanol heavy-duty engine ever sold on a commercial basis, the Model 6V-92TA, but has since discontinued production. The 6V-92TA uses combustion-chamber electric heating elements, called glow-plugs, and careful control of combustion chamber scavenging to ignite the methanol (New York State Energy Research and Development Authority, 1997). Instead of using a special engine, cetane improving additives and minor fuel-injection system modifications allow methanol to be used in any diesel engine. A common ignition-improver is Avocet®, but the cost of Avocet® combined with the already high cost of methanol makes the use of methanol in HDDV impractical from an economic perspective (New York State Energy Research and Development Authority, 1997).

Methanol can be stored in most types of fuel storage tanks. While steel is the preferred material for tanks, a special type of fiberglass has been developed for methanol storage. No aluminum can be allowed in any part of the fuel storage and dispensing system. Methanol will quickly corrode aluminum and aluminum corrosion products will foul filters and engine fuel systems. One difference between methanol and petroleum fuel storage is that methanol is hygroscopic, so exposure to water vapor must be minimized (EA Engineering, Science, and Technolgy, Inc., 1997).

2.2.4.2 Methanol Emissions

For an equal amount of fuel energy, methanol combustion produces 6% less carbon dioxide and carbon monoxide emissions compared to diesel fuel but methanol heavy-duty engines in transit buses have demonstrated fuel energy consumption between 13 and 25% higher than similar diesel engines. The New York State Energy Research and Development Authority found that the straight-methanol engine had much higher unburned fuel emissions than its diesel counterpart (New York State Energy Research and Development Authority, 1997). These emissions are primarily due to the combustion characteristics of the straight-methanol engine, which has higher unburned fuel emissions at low engine speeds and loads. This increase is tempered somewhat by the fact that unburned methanol is less reactive than unburned hydrocarbons from diesel fuel. Emissions of NO for straight methanol were just 25% of those for diesel fuel (EA Engineering, Science, and Technolgy, Inc., 1997).

Particulate emissions of methanol engines are reduced 27% to 40% versus diesel. The reason that particulates are not reduced to zero is that any oil consumed by the engine contributes significantly to particulate emissions. Formaldehyde is a combustion intermediate of methanol and it is not surprising that formaldehyde emissions are a weakness of methanol engines. Conversely, only small amounts of formaldehyde are produced as a by-product of petroleum fuel combustion. Formaldehyde has a pungent odor that tends to make eyes water, and is a suspected carcinogen (EA Engineering, Science, and Technolgy, Inc., 1997).

2.2.4.3 Methanol Production

Methanol is produced primarily from the steam reformation of natural gas (EA Engineering, Science, and Technolgy, Inc., 1997). Methanol is also produced naturally in the anaerobic metabolism of many varieties of bacteria. As a result, there is a small fraction of methanol vapor in the atmosphere. Over the course of several days, atmospheric methanol is oxidized, with the help of sunlight, into carbon dioxide and water. Methanol also can be made from coal, but production from coal is environmentally unattractive because of the significant carbon monoxide emissions released during production (New York State Energy Research and Development Authority, 1997). Methanol can be made from cellulosic wastes such as paper garbage, but the current technology for production is not economically competitive with steam reformation of natural gas (New York State Energy Research and Development Authority, 1997). The largest use of methanol is in production of other chemicals. Approximately 40% of methanol produced is converted into formaldehyde, and from there into products as diverse as plastics, plywood, paints, explosives, and permanent press textiles.

2.2.4.4 Methanol Lifecycle GHG Emissions

For an equal amount of fuel energy, methanol combustion produces less carbon emissions, but this advantage is erased by the additional greenhouse gases produced during methanol production relative to diesel fuel production (New York State Energy Research and Development Authority, 1997). The relative increase in fuel energy consumed for methanol engines also increases the lifecycle GHG emissions (EA Engineering, Science, and Technolgy, Inc., 1997). The overall effect is a substantial increase in lifecycle GHG emissions.

2.2.4.5 Methanol Safety

Methanol is toxic, even fatal, if it enters the body by ingestion, inhalation, or absorption through the skin. It can also lead to the buildup of formic acid and formaldehyde in the liver, which causes permanent blindness. The addition of 15% gasoline makes the fuel smell like gasoline, discouraging consumption (New York State Energy Research and Development Authority, 1997). A methanol flame is almost colorless, causing a safety hazard around open methanol flames.

2.2.4.6 Methanol Social Benefits

US and foreign companies are increasingly building plants for producing methanol, the primary reason being that as a liquid fuel, it is easy to export. Large-scale use of methanol might lessen the transportation sector's dependence on petroleum, but might not lessen U.S.

dependence on foreign energy resources (New York State Energy Research and Development Authority, 1997).

2.2.4.7 Methanol Vehicle Performance

Heavy-duty vehicles using methanol engines have no difficulty achieving the same performance as their diesel-fuel counterparts, partly because methanol combustion does not create soot. Combustion of diesel fuel under heavy engine-load conditions causes soot formation, which must be limited for environmental reasons, and is a major limiting factor on dieselbengine power. Because methanol engines are free of this constraint, they can easily match the power output of their diesel-fuel counterparts. Cold-starting is improved with methanol because of better flow properties at cold temperatures compared to diesel fuel (New York State Energy Research and Development Authority, 1997).

2.2.4.8 Methanol Fuel Costs

Methanol made from natural gas, coal, or other hydrocarbon is expensive and demand in chemical production markets causes the price to fluctuate rapidly. The average price of methanol in 2007 was $1.34 per gallon, or $3.04 per diesel equivalent gallon (Methanex). This represents an increase of approximately 3% versus standard diesel.

2.2.4.9 Methanol Summary

Vehicle modifications for methanol are not costly, much existing refueling infrastructure can be used, and they have attractive emissions characteristics. The higher energy based fuel cost, however, has discouraged potential methanol users. Detroit Diesel Company has discontinued its 6V-92TA methanol engine due to lack of demand and because the diesel engine upon which it is based has been replaced by an improved engine (New York State Energy Research and Development Authority, 1997). Ethanol and methanol are both alcohols and have very similar properties. In general, however, methanol has fewer advantages and more disadvantages as a transportation fuel.

2.2.5 Liquefied Petroleum Gas

LPG stands for liquefied petroleum gas. HD5 is the common standard for LPG used in the US, and requires a minimum propane content of 90%. If the propane ratio is not controlled, the LPG is referred to as autogas (Beer, et al., 2001). LPG, often referred to simply as propane in the US, has been used as a highway fuel for many years by the trucks that deliver bulk propane (New York State Energy Research and Development Authority, 1997). Propane is unique among the alternative fuels in that it is gaseous but becomes a liquid under modest pressure. Although pressure vessels are needed to store propane, the relatively low pressures allow use of inexpensive steel tanks which are lighter than the tanks required to store CNG. The chemical structure of propane is C_3H_8.

2.2.5.1 LPG Technology

LPG is stored onboard vehicles as a pressurized liquid. Storage pressure will depend on the storage temperature and the fuel composition, but pressures are generally less than 250 psi at normal ambient temperatures. LPG storage tanks are required to reserve 20% of their total volume as vapor space to allow for expansion (New York State Energy Research and Development Authority, 1997). Fuels for use in LPG vehicles are required to meet an industry standard called HD-5 or ASTM D1835. This standard limits the amount of propylene and other low octane hydrocarbons. Vehicle fuel systems for LPG vehicles are similar in design to those used for CNG vehicles. Liquid fuel is drawn from the tank and sent to a single unit that lowers its pressure and vaporizes it simultaneously. Engine coolant is used to heat the vaporizer to help prevent freeze-ups (New York State Energy Research and Development Authority, 1997).

Refueling a propane vehicle involves filling the on-board storage cylinder from a dispenser connected to a bulk storage tank. This method takes the same amount of time as refueling a gasoline or diesel vehicle. Propane is stored and handled as a liquid at the refueling station and is pumped from the dispenser storage tank into the vehicle tank (United States Department of Energy).

2.2.5.2 LPG Emissions

Dedicated LPG vehicles do not have evaporative and running-loss emissions because they operate with a closed fuel system (New York State Energy Research and Development Authority, 1997). The low carbon to hydrogen ratio of propane reduces the carbon emissions of LPG vehicles compared to diesel on an energy basis (New York State Energy Research and Development Authority, 1997). Overall emissions from heavy-duty propane engines should be similar to those from heavy-duty natural gas engines assuming the same lean-burn technology is employed. Fuel efficiency of propane heavy-duty engines may be slightly lower than that of natural gas engines because propane has a lower octane value, limiting the compression ratio which can be used (New York State Energy Research and Development Authority, 1997). It is relatively rare for LPG to be used in heavy duty vehicles which results in a lack of published data on the emissions characteristics (Beer, et al., 2001). There is, however, a considerable amount of data in relation to LPG used as fuels in passenger cars (Beer, et al., 2001). Edwards, et al. estimates that LPG will reduce sulfur oxide emissions by 80%, particulate matter by 50%, and have little impact on nitrogen oxides or hydrocarbon emissions for heavy duty engines (Edwards, et al., 2005).

Liquid propane injection is a new technology in which the propane is injected directly into the cylinder in its liquid state. The manufacturers claim it reduces hydrocarbons by 87%, carbon monoxide by 90%, carbon dioxide by 12%, nitrogen oxide by 50% and produce 50% less toxins in heavy duty engines (CleanFuelsUSA, 2007). Using propane to assist in diesel combustion, often referred to as propane fumigation, is another technology which is currently being developed for heavy duty diesel engines by several manufacturers such as Dieselgas (http://www.dieselgas.net/), EcoGas (http://eco-gas.com.au/) and DieselMagnum (http://www.thedieselmagnum.com/). The concept of propane fumigation is not new, but there has not been sufficient independent testing on the products currently available for proper evaluation at this time.

2.2.5.3 LPG Production

Approximately two-thirds of the propane in the U.S. is a by-product of natural gas production, with the remainder being a byproduct of crude oil refining. LPG is distributed throughout the U.S. primarily by pipelines and tanker trucks (New York State Energy Research and Development Authority, 1997). The refueling system for LPG is extensive, primarily due to its non-transportation uses, and there are approximately 3,500 refueling sites in US (Yacobucci, 2005).

2.2.5.4 LPG Lifecycle GHG Emissions

The upstream emissions for the production and processing of propane are lower than they are for diesel and the GHG emissions from the combustion of propane are 16% lower than diesel on an energy basis. The reduction in tailpipe GHG emissions is lost, however, when the lower efficiency of the propane engine is accounted for. The net effect of the fuel production properties and the engine performance is a small decrease in GHG emissions for propane used in heavy-duty engines, which is estimated to be 3% (Edwards, et al., 2005).

2.2.5.5 LPG Vehicle Performance

Using propane may reduce maximum power by up to 7%. This power loss is primarily related to the displacement of intake air by the fuel vapor (United States Department of Energy). In terms of energy content, it takes about 1.4 gallons of propane to equal one gallon of gasoline (New York State Energy Research and Development Authority, 1997). The range of a LPG vehicle is reduced not only because the lower volumetric energy density, but tanks can only be filled to 80% of the tank's full volume to allow for expansion of the fuel (New York State Energy Research and Development Authority, 1997). Residue can build up in the fuel converter of propane-fuel systems must be removed periodically. This residue is believed to be composed of heavy hydrocarbons picked up during production or from transport through pipelines that previously carried distillate or diesel fuel. The propane industry is working on fuel filters for both vehicles and propane dispensers to remove residue and minimize the additional maintenance required (New York State Energy Research and Development Authority, 1997).

Cummins Westport currently produces the most powerful dedicated LPG engine but it is still only 195 hp. High end diesel engines can exceed 450 hp. Lack of suitable equipment limits dedicated LPG technology to smaller heavy-duty vehicle which carry lighter loads. There are propane conversions for heavy-duty engines, but these conversions have had mixed success (Edwards, et al., 2005). Drivers have also noted that when comparing diesel, LPG and CNG in the same engine, the performance ratings are highest for diesel, then CNG, then LPG (Beer, et al., 2001).

2.2.5.6 LPG Safety

Safety considerations for LPG are similar to natural gas, except for the fact that LPG is heavier than air and may accumulate in low lying areas. Propane vapor flammability limits are also wider, which makes LPG ignite more easily. Propane in liquid form can cause cold burns to the skin if handled inappropriately (Beer, et al., 2001).

2.2.5.7 LPG Social Benefits

Since propane is predominately produced as a byproduct of natural gas reserves, there is a large domestic supply of LPG and the social benefits are similar to natural gas.

2.2.5.8 LPG Costs

The capital cost of a Cummins Westport LPG engine is approximately $14,000 higher than the price of a similarly power diesel engine. Changes in LPG prices generally follow changes in crude oil prices. The average cost of LPG in US for 2007 was $2.58 per gallon, or $3.98 per diesel equivalent gallon (United States Department of Energy, 2007). This represents a 35% increase over standard diesel.

2.2.5.9 LPG Summary

LPG has lower peak pressure during combustion than diesel which reduces noise and improves durability. LPG also has low cold-start emissions due to its gaseous state. LPG fuel systems are sealed and evaporative losses are negligible. Propane is also easily transportable and simple and self-contained dispensing facilities available. LPG has lower particulate emissions and lower noise levels relative to diesel, making propane attractive for urban areas, and they do not require special catalysts (Beer, et al., 2001). LPG is the most commonly used alternative fuel and domestic consumption was approximately 242 million gasoline equivalent gallons in 2004. This is greater than all other alternative fuels combined. Propane is primarily used in light- and medium-duty vehicles, and there were approximately 194,000 LPG vehicles on the road in 2004 (Yacobucci, 2005). The population of LPG vehicles has declined in recent years, however, reflecting the lack of available vehicles for sale and the limited market of vehicle conversions (Koyama, 2005). Lack of high horsepower equipment and higher fuel costs are the primary road obstacles for heavy duty LPG vehicles.

2.2.6 Hybrid Technology

A hybrid is defined as carrying at least two sources of motive energy on board and using auxiliary drives to provide partial or complete drive power to the vehicle's wheels. In a series hybrid, only the auxiliary drive powers the wheels and the engine is used to provide energy. In a parallel hybrid, the auxiliary drive and the engine are both connected to the wheels and can both power the vehicle (M.J. Bradley & Associates, Inc., February 2000). Electric drive also allows the recapture of energy that is normally lost as heat in a conventional vehicle via regenerative braking (M.J. Bradley & Associates, Inc., February 2000). A majority of research and development for hybrid technology centers on urban transit buses and package delivery vehicles because their drive cycles provide the best opportunity to leverage the benefits of regenerative braking. Hybrid technology may soon be applicable to heavy duty tractor-trailers in the near future as ArvinMeritor is currently developing a Class 8 diesel-electric hybrid tractor-trailer for Wal-mart (Troy, 2007). Although the hybrid heavy duty vehicles will undoubtedly have different performance characteristics than hybrid transit buses and pack delivery vehicles, the results of studies of these vehicles are presented as an approximation of the performance which could be expected from hybrid tractor-trailers.

2.2.6.1 Electric Hybrid

When an electric hybrid vehicle has a series configuration, an electric motor provides power to the wheels of the vehicle and an auxiliary power unit generates electric power to replace or supplement power from the batteries. In a parallel configuration, the wheels can be driven simultaneously by an electric motor and an auxiliary power unit, typically an engine, depending on the load demand. The drive motor in a parallel hybrid may also spin the motor as a generator and produce power to recharge the batteries. Orion Bus Industries and BAE Systems have developed a hybrid bus using a series design, while Allison Transmission has developed a propulsion system based on a parallel design. (Edwards, et al., 2005). With either a series or parallel hybrid design the vehicle can be powered more efficiently by using regenerative braking to recover some of the kinetic energy otherwise lost during braking, and by reducing the size of the auxiliary power unit or engine.

2.2.6.2 Hydraulic Hybrid

In a full hydraulic hybrid, a hydraulic drivetrain replaces the conventional drivetrain and eliminates the need for a conventional transmission. Hydraulic hybrids store energy in a hydraulic accumulator, which are essentially high pressure nitrogen storage tanks, and use hydraulic pumps to turn the wheel. Hydraulic hybrids can also be arranged in either a series or parallel configuration. Hydraulic hybrids increases vehicle fuel economy in three ways; it permits the recovery of energy that is otherwise wasted in vehicle braking, it allows the engine to be operated at much more efficient modes, and it enables the engine to be shut off during many operating conditions such as when the vehicle is decelerating and stopped at a light (United States Environmental Protection Agency, 2004).

2.2.6.3 Hybrid Performance

The amount of regenerative braking energy recovered is a function of the vehicle's drive cycle. The faster a vehicle decelerates, the less kinetic energy can be recovered due to technological limitations in the vehicle energy storage device and their ability to accept energy quickly. Acceleration on the other hand is usually limited by engine power, or in the case of a hybrid vehicle, drive system power. This is relevant to hybrid buses because the total amount of regenerative braking captured in a hybrid vehicle is limited by the total power handling capacity of the drive motor, controller and batteries. Despite this limitation the total amount of kinetic energy in any given urban cycle is significant and large improvements in fuel economy are expected as a result of recovering just a portion of this energy. Some additional benefit can also be attributed to increased engine efficiency of smaller engines in the hybrid vehicles, which translates into lower idle or dwell losses, although some of this increased engine efficiency is lost due to battery inefficiency (M.J. Bradley & Associates, Inc., February 2000). Electric hybrid buses improve fuel economy approximately 10% compared to clean-diesel buses (Foyt, October 2005). This modest improvement is very similar to that found in current hybrid electric-gasoline engine automobiles in which the same size engine is used in both hybrid and non-hybrid models of the same vehicle (Foyt, October 2005). United Parcel Service is pioneering hydraulic hybrid technology for their urban delivery trucks and report a 60% to 70% increase in fuel economy.

The performance of the hybrid buses is comparable to that of conventional buses and the acceleration of the hybrid buses, especially for a standing start, substantially exceeds that of conventional buses (Foyt, October 2005). A challenging application of a hybrid is in express bus service with sustained highway speeds up long hills. Orion has been able to meet the design requirements in San Francisco for fully loaded buses to handle up to a 21% grade. Drivers in tests in New York City reported that the acceleration, gradability and range of the Orion VI hybrids were as good as or better than the diesel buses and that there were no significant differences in operation (Edwards, et al., 2005).

The primary benefits of series hybrid versus a parallel hybrid configuration are reduced emissions because the engine rarely idles and tends to operates in a narrow peak efficiency band. There is also improved low speed acceleration because all power is routed through the electric motor providing high torque at low speeds. There are numerous component layout options and simpler packaging for series hybrids. The primary drawback of a series configuration is greater energy loss because more energy passes through the energy storage device compared to a parallel hybrid. Another disadvantage of a series configuration is that maximum power at high speeds may only be available with both the auxiliary power unit and the energy storage device operating (Edwards, et al., 2005). Parallel hybrids more offer more overall power because both engine and motor can supply power simultaneously. The weight of the vehicle is also reduced because less energy storage capacity is necessary compared to series hybrid. The biggest trade-off for a parallel configuration is that it is less capable of capturing available regenerative braking energy (Edwards, et al., 2005).

2.2.6.4 Hybrid Emissions

The reduction in carbon emissions for a diesel hybrid is roughly consistent with the improved fuel economy over a standard diesel. Slight nitrous oxide reductions may also be expected because the diesel engines in these hybrid buses are operated in a somewhat more favorable mode (Foyt, October 2005). PM emissions from the hybrid vehicles are generally 50 to 70 percent lower than a conventional diesel (M.J. Bradley & Associates, Inc., February 2000).

Lower emissions are the result of reduced engine transient operation and improved vehicle fuel economy. Hybrid-electric technology demonstrates a measurable advantage in city driving situations, when operated on stop-and-go, low-speed service applications (M.J. Bradley & Associates, Inc., February 2000). While emissions from a conventional engine-powered vehicle rise and fall with power delivered at the rear axle by the engine, emissions from a hybrid vehicle rise and fall with power delivered by the engine, which may or may not follow vehicle speed and load (M.J. Bradley & Associates, Inc., February 2000). Edwards, et al. estimates that a diesel electric bus will reduce sulfur oxides by 30%, particulate emissions by 55%, and hydrocarbons by 45% (Edwards, et al., 2005). Hybrid technology is not fuel specific, so emissions reductions for hybrid vehicles running alternative fuels should reduce emissions even further.

2.2.6.5 Hybrid Lifecycle GHG Emissions

The reduction in carbon tailpipe emissions for hybrid vehicles is proportional to reduction in fuel consumption per mile. Test results also show that GHG emissions from hybrid transit buses are 32% lower than a diesel busses under a standard drive cycle (Edwards, et al., 2005). This benefit will be offset, however, by the emissions and energy associated with production of the additional hybrid equipment.

2.2.6.6 Costs

A hybrid electric bus is estimated to cost approximately $315,000 more than a convention diesel bus and there is also an infrastructure costs required to accommodate the electrical equipment and wiring needed for battery equalization and charging (Edwards, et al., 2005). Based on current information and on projections for fuel and maintenance costs, the total lifecycle cost of ownership for a hybrid bus is estimated to be substantially higher than that for the conventional clean-diesel bus unless a federal subsidy is included (Foyt, October 2005). The current expectation is that the battery pack will need replacement after six years of service but the reliability data for nickel-metal-hydride batteries have been very good in hybrid automobiles (Foyt, October 2005).

2.2.6.7 Hybrid Summary

Hybrid technology for heavy duty applications, other than transit busses, has not been sufficiently developed at this time. Packaging energy storage devices and drives into tractor-trailers without sacrificing storage capacity is currently the largest obstacle which must be overcome. The drive cycle of most HDDV applications, however, provide sufficient opportunity to capture energy via regenerative braking which makes hybrid technology very attractive for the future.

2.2.7 Clean Diesel and Retrofit Technology

Retrofit projects can begin producing emission reductions immediately and can help state and local governments reduce emissions of particulate matter, nitrogen oxides, and volatile organic compounds in the near term. Retrofits include a wide range of emission reduction strategies available for diesel vehicles and equipment, including; retrofitting engines with verified technologies, replacing older equipment, repowering old vehicles with new engines, reducing idling, properly maintaining equipment, and gaining operational efficiencies (United States Environmental Protection Agency, 2007).

The Energy Policy Act of 2005 includes a Diesel Emissions Reduction Program that authorizes funding to establish cost-effective clean diesel projects. Retrofit projects can begin producing emission reductions immediately and can help state and local governments reduce emissions of particulate matter, nitrogen oxides, and volatile organic compounds in the near term (United States Environmental Protection Agency, 2007). The Clean Diesel technologies considered in this analysis are; changes to diesel fuel quality, diesel-water emulsifications, particulate matter traps, and oxidation catalysts.

2.2.7.1 Diesel Quality changes

Detergents can be added to diesel fuel in order to clean-up diesel injectors or keep them free of deposits. Heavy-duty engines that have clean fuel injectors provide better performance than engines with dirty injectors. The emission reductions available through the use of detergents are mostly a function of the level of deposits that have built up on the injectors. Use of detergents in a new engine, which have no deposits, is unlikely to reduce emissions but will help maintain low emissions as the engine ages. Cetane improving additives can provide some performance benefits as engines are generally easier to start and can have less combustion noise and smoke. Nitrous oxide emissions also fall when the cetane number is increased (Edwards, et al., 2005).

Diesel fuel sold in California is known as CARB diesel and it is specially formulated to have a lower aromatic content and higher cetane number than the diesel fuel found in other parts of the US. According to the EPA, CARB diesel produces emission reductions of 6.2% for nitrous oxides, 8.5% for particulate matter and 19.4% for hydrocarbons compared to standard diesel. CARB diesel is, however, generally more expensive (Edwards, et al., 2005).

The upper limit of regulated sulphur content of diesel fuel was reduced from 500 ppm to less than 15 ppm in 2007. This ultra low sulphur diesel fuel (USLD) enables several new diesel emission control strategies, such as diesel particulate, to be introduced into the market. Ultra low sulphur diesel fuel will have slightly higher greenhouse gas emissions than standard diesel to do increase process requirements and slightly reduced vehicle efficiency (Edwards, et al., 2005).

Lowering the density of diesel can reduce nitrous oxides and particulate matter emissions but also lowers the energy content. When the density of the fuel is lowered, the hydrogen to carbon ratio of the fuels increases. Increasing this ratio offsets the negative effects of higher volumetric fuel consumption on carbon emissions (Edwards, et al., 2005). Table 6 hows the expected change in tailpipe emissions for the various changes in diesel fuel quality (Edwards, et al., 2005).

Table 6 Expected Emissions Reductions from Diesel Fuel improvements

Emissions	Low Sulfur	Low Density	CARB Diesel	Detergents	Cetane Additives
SO_X	-95%	6%	No change	No change	No change
PM	-2%	-11%	-9%	-5%	-2%
NO_X	No change	-7%	-6%	-10%	-3%
HC	No change	No change	-19%	-7%	-15%
GHG	3%	No change	Higher	-2%	no change

2.2.7.2Diesel-Water Emulsion

PuriNOx™ is a diesel water emulsion product developed by Lubrizol Corporation. The system uses a combination of proprietary additives and a mechanical blending system to produce the final product (Lubrizol, 2001). Chevron markets the fuel in California using the brand name Proformix™. Diesel water emulsions can reduce particulate emissions up to 50% and reduce nitrous oxides up to 15% in heavy-duty diesel engines (Edwards, et al., 2005). PuriNOx™ can be any combination of the additive, but is typically 20% water. The US EPA has approved PuriNOx™ as a verified technology in their diesel retro-fit program and it is generally compatible with most diesel powered vehicles. The vehicle will, however, experience up to a 20% loss in maximum engine horsepower. Given that the PuriNOx™ contains 20% water by volume, the fact that the volumetric fuel consumption only increases by 15% indicates that there is a slightly higher thermal efficiency experienced with the PuriNOx™. The fuel economy change is likely to depend on the duty cycle, with the lowest efficiency gained while operating at wide open throttle (Edwards, et al., 2005). Diesel water emulsions typically cost the same, or slightly more, per gallon than comparable diesel fuel, yet the energy content of the fuel is lower. Overall, it is estimated that diesel water emulsions have an additional cost equivalent to $0.25 per diesel equivalent gallon of fuel, which corresponds to a 15 – 20% increase in fuel costs on an energy basis. (Edwards, et al., 2005)

2.2.7.3 Particulate Matter Filters/Traps

Early diesel particulate filters (DPF), also known as traps, suffered from problems with poor reliability and durability. New generation DPF are designed to overcome the old design pitfalls by using passive or active regeneration to remove accumulated carbon from the filter.

Passive regeneration of elemental carbon occurs when the exhaust temperature reaches 600ºC and there is enough oxygen to oxidize the elemental carbon trapped in the filter.

In diesel engines, there is always sufficient oxygen for regeneration to occur but exhaust gas temperatures near 600ºC are rarely reached. Consequently, passive regeneration is difficult to achieve under normal operating conditions and means are needed to lower the temperature required to initiate the reaction, or supplemental heating is necessary to reach PM regeneration temperatures. Using other means to increase the exhaust temperature is called active regeneration, such as electrical heating or full-flow burners (Edwards, et al., 2005).

Passive regeneration can occur if the elemental carbon is oxidized at lower temperatures via a catalytic reaction. Passive regeneration can be achieved by placing a catalyst upstream of a DPF, sometimes referred to as catalyzed soot filter (CSF). The catalyst will oxidize NO to NO_2 and then NO_2 will react with the carbon particles trapped in the DPF yielding CO_2 and nitrogen (Edwards, et al., 2005).

Filtration efficiency is an important measure of DPF performance. Filtration efficiency is the ratio between the PM trapped in the filter to the total PM passed through. DPF efficiencies range between 80 and 98% (Edwards, et al., 2005). Filter efficiency usually increases with use, because particles build up within the filter media. High filtration efficiency is associated with high backpressure and consequently high fuel consumption and loss of power. Therefore, most of DPF manufacturers recommend installing a back-pressure sensor to minimize any negative impacts. According to a US EPA study of retrofit diesel particulate filters, a particulate matter reduction of up to 90% is achievable, while at the same time reducing CO and HC emissions by between 50-90%.

The suitability of a DPF retrofit depends on fuel sulphur content, exhaust temperature, vehicle application and engine year. DPFs require periodic maintenance to maintain their efficiency and service life. The recommended fuel for use of a catalyzed DPF (CRT) is diesel fuel having a sulphur content of 15 ppm, or less. As the fuel sulphur content increases above this recommended level, the efficiency of the DPF deteriorates, and at high levels, a permanent loss in performance can result. (Edwards, et al., 2005).

There will be an increase in fuel consumption between 1 and 4% is expected when using a DPF due to the increase in fuel consumption which results from higher engine backpressures. The capital cost of the DPF is estimated to be between $4,000 and $5,500, which corresponds to a cost of $0.025 per mile (Edwards, et al., 2005).

2.2.7.4 Oxidation Catalysts

Oxidizing catalysts (OC) are one of the oldest after treatment devices used to control engine exhaust emissions and are used on most gasoline vehicles in North America. The OCs used with gasoline engines are often called 3-way catalysts, while those used with diesel engines are called DOC or 2-way catalysts. Both have the same operation principle, but 3-way catalysts oxidize three pollutants (HC, NOx and CO) and 2-way catalysts oxidize only two pollutants (HC and CO). There is a fundamental difference between the operation principle of DOCs and catalyzed soot filters. CSF oxidizes the soot, or elemental carbon, trapped in the filter media with the aid of a catalyst at a lower temperature than the temperature that would otherwise be required. DOCs oxidize only the soluble organic fraction of particulate matter. DOCs have a lower efficiency than a CSF, as the soluble organic fraction constitutes only 25 - 40% of the total particulate matter composition. DOCs also may oxidize sulphur dioxide to sulphate, which offsets some of the PM reduction. The sulphate compounds also react with water to form sulphuric acid, causing catalyst poisoning (Edwards, et al., 2005).

In a study of retrofit technology preformed by the EPA, DOCs were retrofitted in 60 heavy-duty diesel 4 and 2 stroke engines. Using DOCs with these engines achieved reductions in particulate matter emissions ranging from 19 to 50%, with an average reduction of 33%.

DOCs also achieved HC and CO reductions of 50-90% and 45-90%, respectively. An increase of 1-2% in GHG is expected with DOCs because of the increase in fuel consumption resulting with higher engine backpressure (Edwards, et al., 2005).

2.2.7.5 Clean Diesel Summary

The EPA has developed a list of verified retrofit technologies that contains information on expected emission reduction benefits. This list provides information on numerous innovative emission control technologies that the EPA has approved for receiving emission reduction credit. Each EPA verified technology has undergone extensive testing and analysis. The verification process includes evaluations of the emissions reduction performance of retrofit technologies and identification of engine operating criteria and other conditions that must exist for these approved technologies to achieve the verified level of reductions (United States Environmental Protection Agency, 2007). The US EPA SmartWay program is designed to help truck owners compare the costs and estimate the fuel savings associated with various efficiency technologies (United States Environmental Protection Agency, 2007). EPA verified technologies include; direct-fired heaters which are stand-alone units capable of providing heat to vehicles in cold weather, automatic engine idle devices which shut off engines when they are not being used, auxiliary power units which are small electric generators that provide power for air conditioning or heating while the main engine is turned off, and truck stop electrification which provides sources of electricity to parked trucks so that drivers do not need to idle their engines.

2.3 Literature Review Summary

This literature review is divided into two sections; one section examines the social and environmental impacts of emissions and the other section examines candidate alternative fuels and technologies. The social and environmental impacts include sources of mobile emissions, types of emissions considered, environmental and sociological effects. The alternative fuels and technologies section gives an overview of the potential candidates for the large automotive manufacturer's specific application and provides the necessary information to complete the emissions and cost indices as well as the decision matrix.

The emissions considered in this TBL method are those defined by the EPA as criteria pollutants which include carbon monoxide, nitrogen oxides, sulfur dioxides, ozone, and particulates. Carbon dioxide is considered in the TBL analysis because of the significant impact it has on the environment. Short term health effects of inhalation exposure to diesel exhaust include eye, throat and bronchi irritation, neurophysiological symptoms such as headaches, light-headedness, fatigue, abdominal discomfort and nausea and respiratory symptoms such as coughing and phlegm. Long term health effects of diesel exhaust are associated with particulate matter, carbon monoxide, and the ground level ozone, which is produced by volatile organic compounds and nitrogen oxides. Some of the important consequences of reactivity include formation of ozone, smog, and acid rain. Smog is a brownish haze in the air that forms in highly polluted metropolitan areas. Its main unhealthy ingredient is ground-level ozone.

The candidate alternative fuels and technologies presented in this section are selected based on a broad literature survey of applications involving the replacement of diesel in heavy-duty vehicles. Sources of application information are informal, including EPA factsheets, equipment manufacturer's catalogs and websites, trade organization newsletters, journal articles, news reports and various presentations given by people in industry. Biodiesel, Natural Gas, Ethanol, Methanol, and Liquefied Petroleum Gas were identified as possible fuels for

HDDV by the initial literature survey and Hybrid and Clean Diesel are identified as possible alternative technologies. It is important to note that these are broad categories, and there are many subsets within each one. Biodiesel, for example, may be used neat, or mixed with diesel fuel in varying amounts. A literature review of each fuel or technology will be presented in this section including the emissions performance, production method, safety, social benefits, vehicle performance, associated costs, and a summary of the each fuel's overall performance

CHAPTER 3 SURVEY OF HDDV CARRIERS

It is necessary to benchmark the environmental performance and the level of alternative fuel and technology which is currently being used in the target application before the potential benefits of introducing a new technology can be accessed. Since the large automotive manufacturer contracts independent carriers for a majority of its inbound shipments, a direct web-based survey is used to accumulate the desired data. This data includes statistics on environmental impact programs, idle reduction policies, emissions reduction equipment, and alternative fuels. Additional data on vehicle classes, fleet composition, vehicle performance and types of shipping lanes are used in defining the scope of the target application and identifying technologies which are applicable. This survey also offers a means to infer qualitative conclusions regarding the implementation of new technology such as: local availability, relative costs, performance impacts, and level of interest. The first section in this chapter discusses the architecture of the survey and presents the results in graphical form. Results are analyzed with respect to the expected outcome and potential impacts on a TBL business case. The second section in this chapter presents a similar analysis of several relevant cross tabulations of the survey data. The company's entire carrier network for the Michigan area received the survey, which are 62 carriers in total. Responses were received from 32 carriers, including 8 of the top ten carriers. The survey was distributed in June of 2007 and the survey results were tabulated in October of 2007.

3.1 Survey Architecture and Results

The survey questions are divided into two general sections: one section for carrier data and the other section for alternative fuels and technology. Carrier data is necessary to compare the performance of carriers relative to each other. The questions are designed to ascertain statistics on fleet composition, owner operator percentage, types of shipping lanes, and average mpg. The average mpg is used as the measure of effectiveness while the fleet composition and business type are necessary to frame the results in cross tabulations.

Alternative fuel and technology questions are designed to ascertain statistics on alternative fuel availability, utilization of emissions equipment, and environmental programs and policies. This data is useful as a benchmark for technologies and programs currently being implemented. Correlating the alternative fuel data with the performance metrics from the carrier data provides a method for drawing qualitative assessments of alternative fuels and technologies, emissions equipment, and various programs and policies.

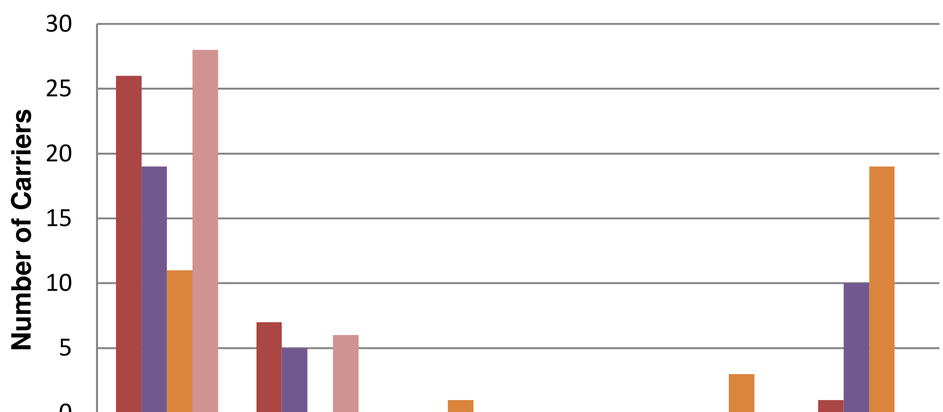
3.1.1 Carrier Data

This section gives greater detail on the questions carriers were asked regarding their fleet composition, owner operator percentage, business type, and miles per gallon. The results are presented in the form of histograms which give the number of carriers falling into each bin for a particular question.

3.1.1.1 Fleet Composition

Carriers are asked to identify what percentage of their fleet are Class 7 (Four-axle single unit), Class 8 (Less than five-axle tractor/single trailer), Class 9 (Five-axle tractor/single trailer, “18 Wheeler”), and Class 10 (More than five-axle tractor/single trailer). These vehicle classes are chosen because they encompass a majority of the target application and are typically handled by heavy duty diesel vehicles. For each vehicle class, carriers select a percentage which reflects their fleet composition. The average fleet composition for the carriers surveyed is 5% Class 7, 25% Class 8, 67% Class 9, 1.3% Class 10, and 1.7% other.

This information is useful because certain alternative fuels and technologies have limitations specific to vehicle classes. Limitations can include, but are not limited to, equipment availability, power requirements, government regulations and safety. Battery-electric power, for example, may be available for a Class 7 short haul delivery tuck but not Class 9 tractor trailers due to power limitations of the technology. A histogram for the fleet composition survey result is shown in Figure 4.1. The fleet composition statistics are broken down into six bins which represent 0%, 0-20%, 20-40%, 40 -60%, 60-80% and 80 -100% fleet composition for each vehicle class and the number of vehicles in each bin is shown on the vertical axis.



	0%	0 - 20%	20 - 40%	40 - 60%	60 - 80%	80 - 100%
Class 7	26	7	0	0	0	1
Class 8	19	5	0	0	0	10
Class 9	11	0	1	0	3	19
Class 10	28	6	0	0	0	0

Figure 3.1 Histogram of Fleet Composition

Since many carriers specialize is certain vehicle types, the histogram shown above is useful for determining the number of carriers who have percentage of their fleet composed of a certain type of vehicle. The results shows that almost all carriers have less than 20% of their fleet composed of Class 7 or Class 10 vehicles. This result is significant because it implies that Class 7 and Class 10 vehicles represent a very small opportunity for the implementation of alternative fuel and technology and should be given a lower priority for analysis. The fleet composition results indicate that there are 10 carriers whose Class 8 fleet composition is higher than 80%. If a carrier owns Class 8 vehicles it is very likely that they are specialized to run Class 8 vehicles. A similar conclusion can be drawn for Class 9 vehicles. This implies that an alternative fuel or technology targeted at either Class 8 or Class 9 vehicles is likely to apply to the entire fleet which may provide significant economies of scale.

3.1.1.2 Owner Operator percentage

An owner operator is a person who owns their own equipment. An owner operator is free to either haul free-lance, or enter into a lease agreement to dedicate their equipment to one customer, product, or a larger carrier service. The situation where the carrier company owns the vehicle and simply employs the operator is referred to as a privately owned vehicle. Carrier's fleets can range from fully private to those which are 100% owner operator. Carriers are asked what percentage of their fleet are owner operators and Figure 4.2 shows a histogram of their responses. The results show that 8 carriers are composed entirely of owner operators and that 8 carriers have no owner operators at all. The remaining 18 carriers have mixed fleets.

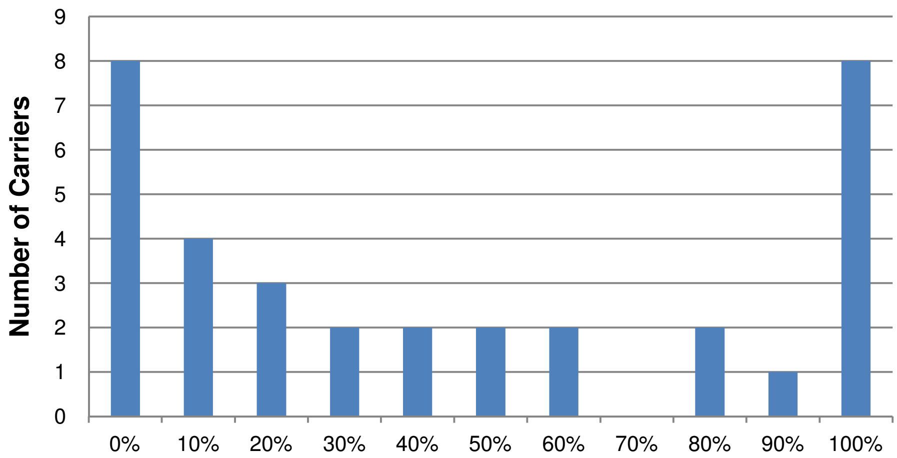
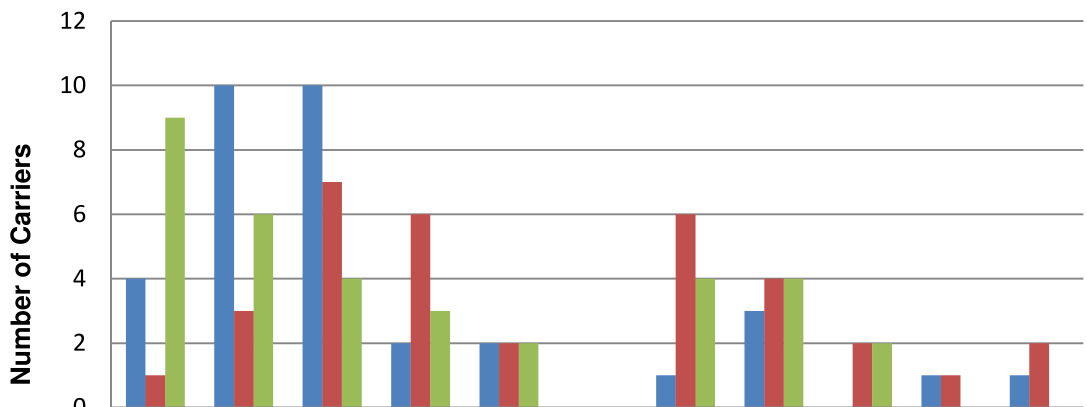


Figure 3.2 Owner Operator Percentage

An owner operator typically has to pay higher rates to insurance companies due to their smaller size. This may cause them to charge more to balance the cost. They subsequently carry more burden than larger trucking companies but also enjoy a larger portion of its proceeds. The percentage of a carrier's fleet which is owner operator can therefore have a large impact on the funds available to invest in new technology as well as the potential return on investment. On the other hand, carriers which own large fleets may enjoy better economies of scale on alternative fuel or technology investments and incur less risk when running test pilots. Since the impact of owner operator percentage is ambiguous, it is good candidate for cross-tabulation.

3.1.1.3 Type of Shipping Lane

Shipping lanes can be broken into three general categories: Short, Medium and Long Haul. For this survey, Short Haul is defined as any shipment whose round trip distance is less than 100 miles, Medium Haul is between 100 and 500 miles, and Long Haul is greater than 500 miles. The survey participants are asked what percentage of their business falls into these three categories and a histogram of the results is shown in Figure 4.3. The statistics are divided into bins which represent 0%, 0-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%, 80-90% and 90-100% of the carrier's total business and the number of carriers is represented on the vertical axis.



	0%	0 - 10%	10 - 20%	20 - 30%	30 - 40%	40 - 50%	50 - 60%	60 - 70%	70 - 80%	80 - 90%	90 - 100%
Short Haul	4	10	10	2	2	0	1	3	0	1	1
Medium Haul	1	3	7	6	2	0	6	4	2	1	2
Long Haul	9	6	4	3	2	0	4	4	2	0	0

Figure 3.3 Histogram of Business Type: Short, Medium, and Long Haul

These results indicate that a majority of the carriers have less than 30% of their business composed of Short and Long Haul shipping lanes. This data is particularly useful when trying match prospective technologies with carriers. For example, 3 carriers have Short Hauls percentages higher than 80% which make them ideal candidates for technologies with limited range, such as compressed natural gas. It is also important to note that none of the carriers surveyed specialized in Long Haul shipments, which can have a significant impact on the rate of return for many technologies, especially those which deal with idle reduction.

3.1.1.4 Average Miles per Gallon

The carriers are asked for their average miles per gallon, or mpg, for Short, Medium, and Long haul shipments. The rationale behind this differentiation is based on the fact that different shipment types encounter substantially different drive cycles. A histogram of the survey responses for average mpg is shown in Figure 4.4. The statistics are organized into bins in 0.2 mpg steps ranging from 5 to 7 and the number of carriers is on the vertical axis.

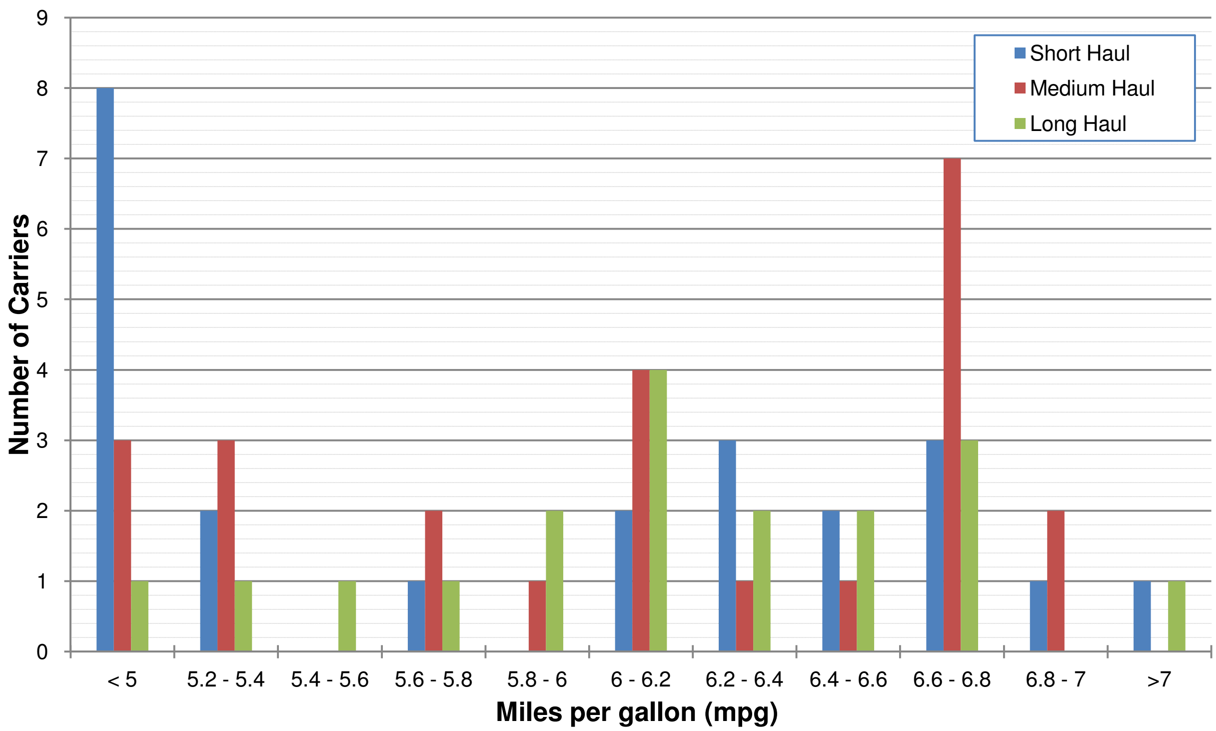


Figure 3.4 Histogram of Average MPG for Carriers

Short Haul lanes are expected to have the lowest average mpg of any shipment type because they spend a higher percentage of their time loading and unloading cargo which increases the percentage of idle time. Short Haul lanes are also expected to operate on surface streets which operate at slower speeds and have more start and stops, all of which should have a negative impact vehicle mileage. Long Haul shipments often have additional idle time associated rest stops, tolls, traffic, refueling, etc which decrease mpg, but Long Haul shipments also enjoy a high percentage of highway miles which increases mpg. Since Medium hauls also enjoy moderate percentage of highway drive time, the relative mpg difference between Medium and Long Hauls is ambiguous and make good candidates for cross tabulation.

When comparing the number of carriers reporting less than 5.0 mpg, it is clear the Short Haul dominates the category with 8 compared to 3 and 1 for Medium and Long Haul respectively. This is consistent with expectations. There appears to be a trend in mpg for Medium Haul mpg, centering around 6.2 - 6.4 mpg and tapering to the boundaries. There is no clear trend for Long Haul in this data set.

The distribution of the responses for average mpg is shown in Figure 4.5. Each carrier's response is organized in vertical columns. It is important to note that not every carrier provided data for each shipment type. The Short, Medium and Long Haul average mpg for all carriers is 5.5 ± 0.98, 6.0 ± 0.72, and 6.2 ± 0.72 respectively. The average mpg, weighted by the percentage of Short, Medium, and Long Haul business, is 5.9 ± 0.74 mpg. The expected mpg for a heavy duty diesel vehicle is 6.2 mpg as calculated by the EPA's emission modeling software Mobile 6.2, which is discussed in further detail in Chapter 5.

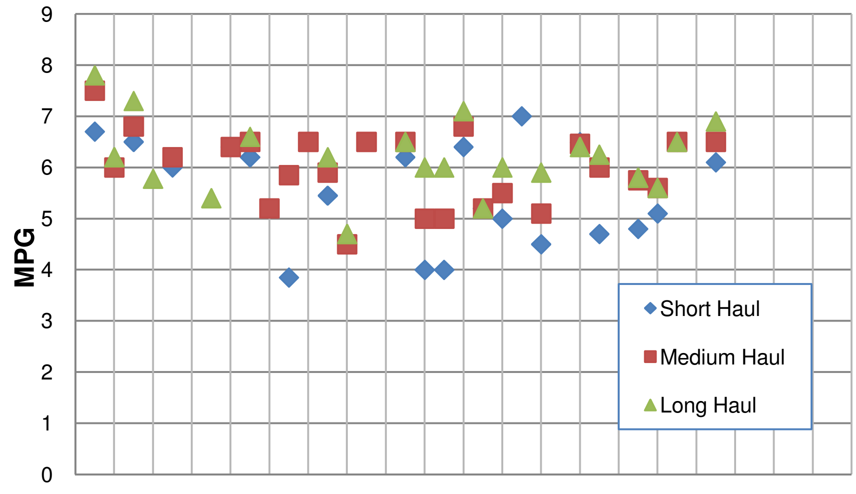


Figure 3.5 Distribution of Average MPG for Carriers

3.1.2 Alternative Fuel and Technology

This section gives greater detail on the questions carriers are asked regarding alternative fuel availability, environmental impact programs, idle reduction policies, and emission control equipment. The results are presented in the form of histograms which give the number of carriers which fall in the appropriate bins for a particular question.

3.1.2.1 Alternative fuel availability

Each carrier is asked which alternative fuels are locally available at the time the survey is conducted. The carriers are asked specifically about biodiesel, ethanol, hydrogen, propane and compressed natural gas. These fuels are chosen because they have been identified as the most likely to be commercially available. Carriers are also asked to name any additional fuels available to them. A histogram of the response is shown in Figure 3.6.

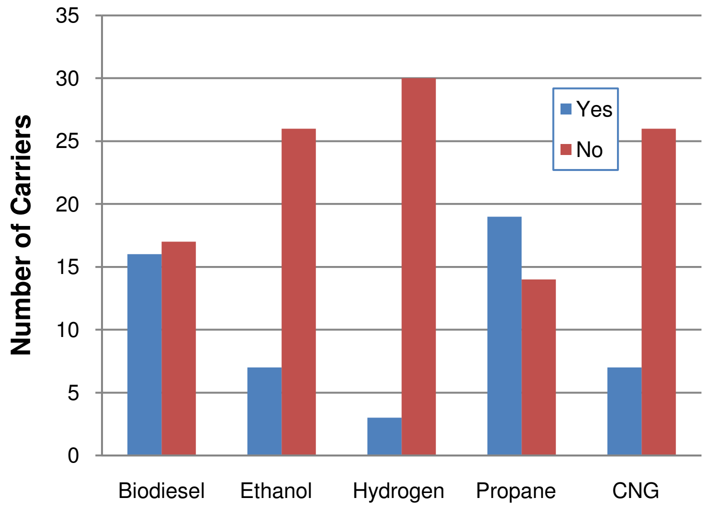


Figure 3.6 Alternative Fuels Available to Carriers

Approximately half of the carriers have commercial sources of biodiesel and liquid propane gas, but only a small percentage had ethanol, hydrogen, or compressed natural gas available. This data is congruent with expectations because LPG is the third most commonly used transportation fuel in the US and biodiesel blends can be utilized in the existing diesel infrastructure. This data also confirms the expectation that the operation of hydrogen of CNG will require significant facility investment to support fuel distribution. The low percentage of ethanol availability, however, indicates that ethanol-diesel blends have not gained wide spread acceptance. E-diesel, therefore, is not a likely alternative fuel candidate due to a lack of infrastructure.

Seven Carriers indicated that they currently use a Biodiesel blends in their fleets. Usage varied in magnitude between 5% and 100% of fleet vehicles and all carriers reported that the cost of biodiesel was equal to or less than convention diesel and they reported no maintenance cost increase. This result is contrary to the anticipated outcome because the national and regional average for biodiesel is higher than diesel.

3.1.2.2 Programs and Policies

Each carrier is asked if they have programs or policies for the use of low sulfur diesel, clean diesel technology, and alternative fuels. They are also asked if they had policies for the reduction of idle time and environmental impact. A histogram of the carrier responses is shown in Figure 3.7. The data reveals that a majority of carriers have policies for the use of ultra low sulfur diesel and idle reduction policies. This is consistent with expectations because the use of ultra low sulfur diesel is going to be mandated by the U.S. government and idle reduction policies are likely to provide an economic benefit to the carrier. Carriers are also asked to give a brief description of each program and policy.

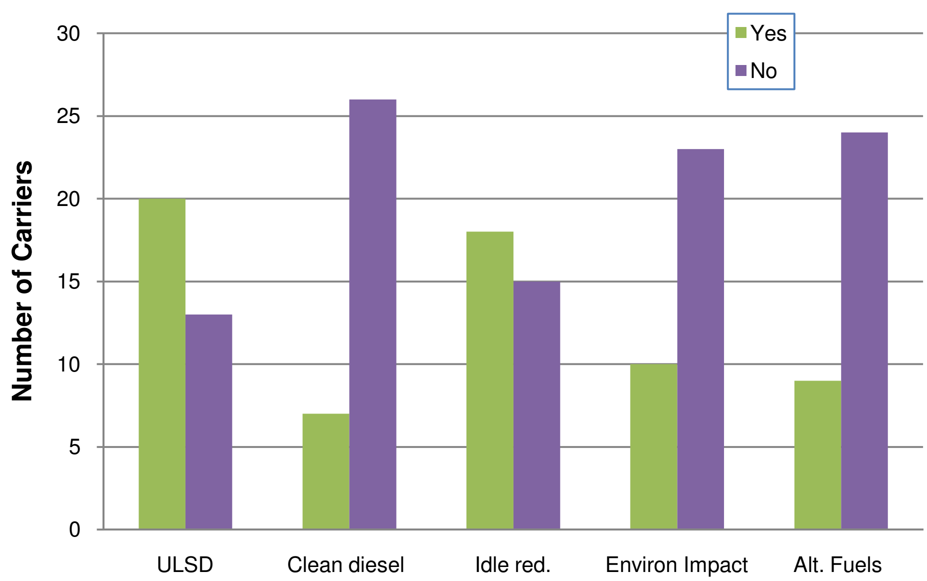


Figure 3.7 Programs and Policies of Carriers

Several carriers indicated that their trucks shut off automatically after 3 minutes of idle time, others indicate as much as 30 minutes before automatic shut off. Additionally, thermostats provide auto restart if the engine temperature drops too low. Carriers without automatic shutoff indicate that drivers should shutoff during any period of comfortable weather or indicate the use of either truck stop electrification or APUs. Some carriers indicate they use sensors to calculate idle time percentage and enforce driver compliance. Another interesting policy involves reimbursing the fuel cost to owner-operators on mileage basis only, increasing the driver's incentive to reduce idle time. Other fuel saving initiatives include governing the speed of trucks, driver incentive programs based upon mpg archived, engine block heaters, tire checking programs, driver training, progressive shifting, and vehicle alignments.

Alternative fuel programs generally consist of running controlled tests on small numbers of vehicles and tracking fuel usage and performance issues. Several carriers also indicated interest in hybrid powered vehicles. Due to warranty concerns, many carriers look toward their engine manufacturers for alternative fuel options. Most carriers cited cost and availability of technology as the most significant barriers to the implementation of alternative fuels.

Of the carriers with environmental impact programs, most cite ISO 14001 or the EPA SmartWay Program as their primary guidance. Carriers using clean diesel technology indicated that maintenance costs increase. This is consistent with expectations because these technologies are additional equipment which must be serviced and replaced on regular intervals. Carriers are also asked to include a brief description any additional environmental impact programs and policies, examples include: using a 15 % ethanol mixture in their diesel fuel, oil and antifreeze recycling, governing trucks, engine block heaters, tire checking programs, engine tune ups, driver training, progressive shifting, radio frequency tags to bypass tollbooths and truck stops, and carbon credit trading.

3.1.2.3 Programs and Policies

Carriers are asked what percentage of their fleet are equipped with fuel saving and emission reduction equipment including; auxiliary power units, aerodynamic retrofits, automatic tire inflation, single wide tires, particulate matter traps, and weight reduction. Figure 4.8 shows a histogram of the responses.

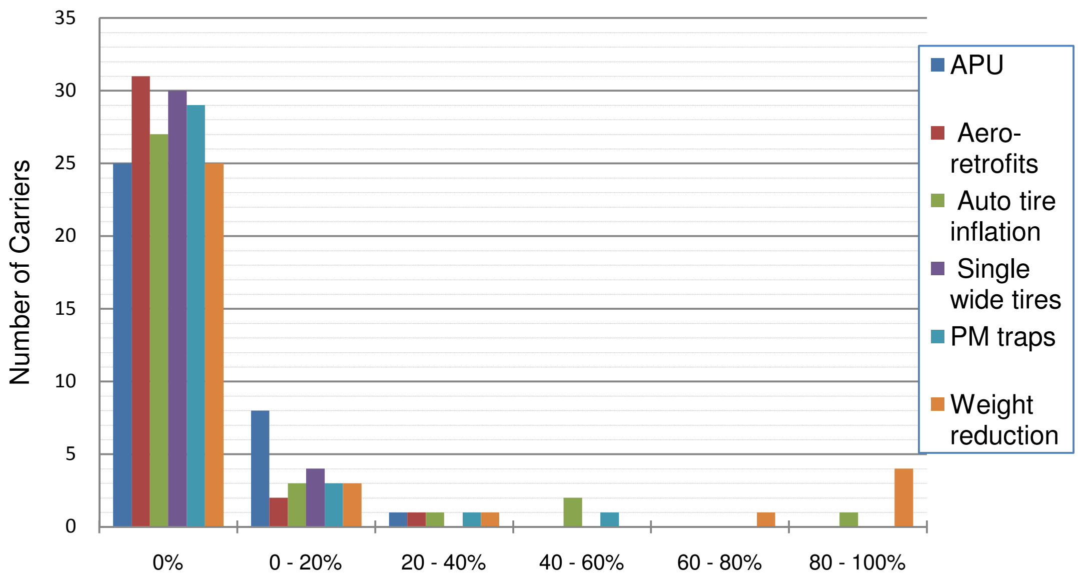


Figure 3.8 Emissions Equipment

It is clear that a very low percentage of most carriers' fleets are equipped with any of these technologies. This represents a significant opportunity for increasing the fuel efficiency and environmental performance of these carriers.

3.2 Cross Tabulations

Several cross-tabulations are of particular concern. It may be important to know whether or not certain technologies are implemented more often on Class 8 vehicles, or if carriers with lower owner-operators percentages have better environmental impact programs. The effect of vehicle class and owner operator percentage also may have a large impact on the mpg of a carrier. Cross tabulations for owner operator percentage, fleet composition, programs and business type are presented in this section.

3.2.1 Owner Operator Percentage

3.2.1.1 Mileage versus Owner Operator Percentage

The percentage of owner operators that a carrier employs may have a significant impact on the fleet's average fuel economy. The method for compensating drivers for fuel usage may encourage drivers to implement fuel savings initiatives. If owner operators are only compensated on a per mile basis, the driver has more incentive to save fuel. On the other hand, drivers who work directly for the carrier may be subject to strict policies for the reduction of fuel consumption which is enforced by the carrier. There are also differences in maintenance schedules, age, and technology between carrier and owner operator vehicles which may affect average mpg. It is also possible that carriers are reporting the rate at which they reimburse drivers for fuel costs, not the actual mpg achieved. Figure 4.9 shows the owner operator percentage versus the average mpg reported by the carriers for short, medium, and long haul shipping lanes. The only apparent trend in these results is that carriers with either very high or very low owner operator percentages have worse average fuel economies than carriers with mixed fleets and that short haul shipments have the lowest mpg, followed by long hauls.

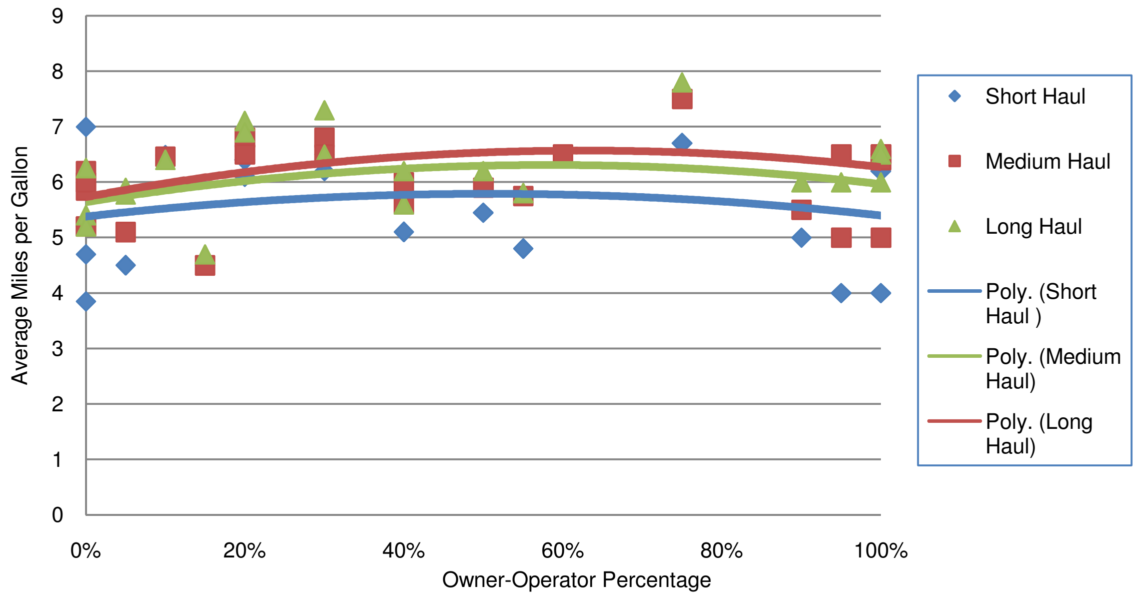


Figure 3.9 Mileage versus Owner-Operator Percentage

The carriers are divided into four subgroups, each of which contains between 8-9 carriers. Dividing the carriers in this manner results in subgroups which contain 0%, 0 - 30%, 30-90%, and 90-100% owner operator percentage. The average mpg for each subgroup is then calculated and is shown in Figure 4.11. These results indicate that carriers with owner operator percentages between 0 - 30% have the best fuel economy and carriers with 0% owner-operators have the worst fuel economy. These results indicate that there may be an underlying trend which improves the fuel economy of fleets which have owner-operators, but only in small percentages.

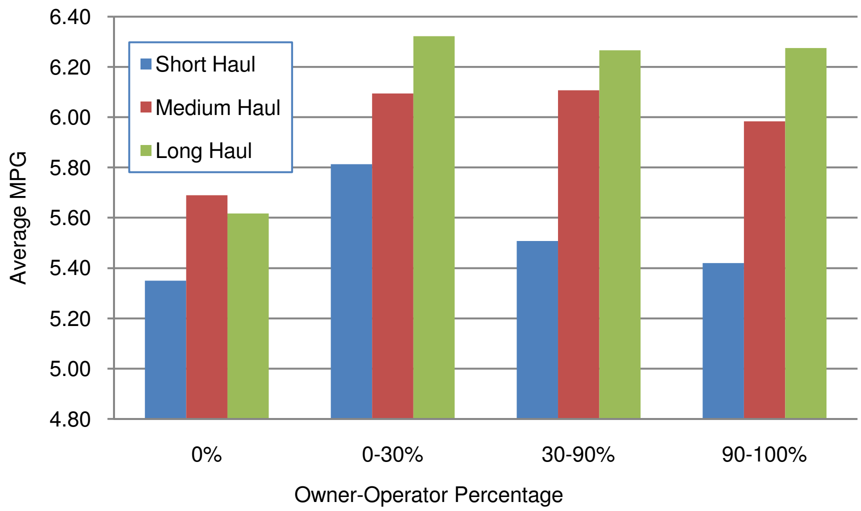


Figure 3.10 Average MPG versus Owner Operator Percentage

3.2.1.2 Fleet Composition versus Owner Operator Percentage

The owner operator percentage may have a significant impact on the type of vehicles that a carrier uses. The price of the vehicle, maintenance cost, or profitability all may a have a significant impact on the incentive for an owner operation to choose one vehicle class over another. Carriers are divided into four equal subgroups using the same percentages described in the previous section. Figure 4.10 shows the average fleet composition for class 8 and class 9 vehicles for these subgroups. Class 7 and class 10 vehicles are not included in this plot because they do not appear in significant percentages.

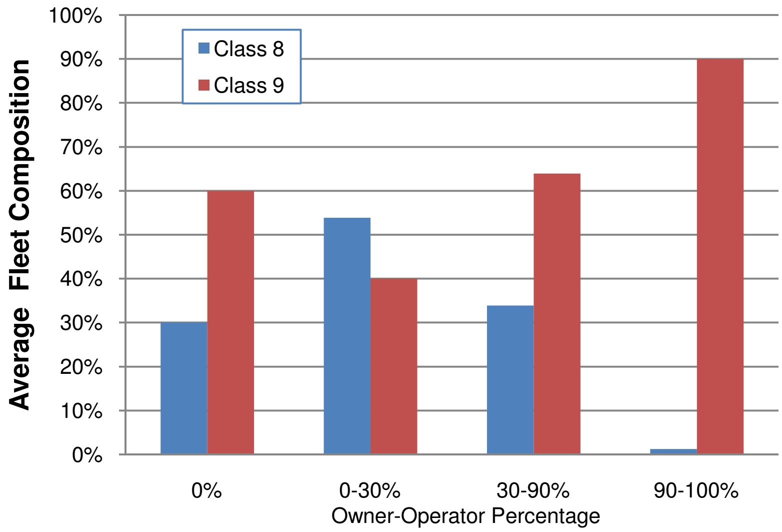


Figure 3.11 Average Fleet Composition versus Owner Operator Percentage

It is clear that those carriers which are composed of more than 90% owner operators run class 9 vehicles almost exclusively. It is also interesting to note that the only subgroup which has a higher percentage of class 8 vehicles, 0 - 30%, also had the highest average mpg. These class 8 vehicles may be particular attractive to owner-operators because of the higher mpg which is achievable.

3.2.1.3 Programs and Policies versus Owner Operator Percentage

The owner operator percentage may have a significant impact on the level of use of emissions equipment, alternative fuels, idle reduction policies, and environmental policies. The price of the vehicle, maintenance cost, or profitability all may a have a significant impact on the incentive for an owner operation to implement these programs, policies, and technologies. Figure 3.12 shows the carriers responses for the same owner operator subgroups described in previous sections. The emissions equipment percentage is an average of all the vehicles equipped with technologies designed to reduce vehicle emissions. The individual technologies are described in greater detail in previous chapters.

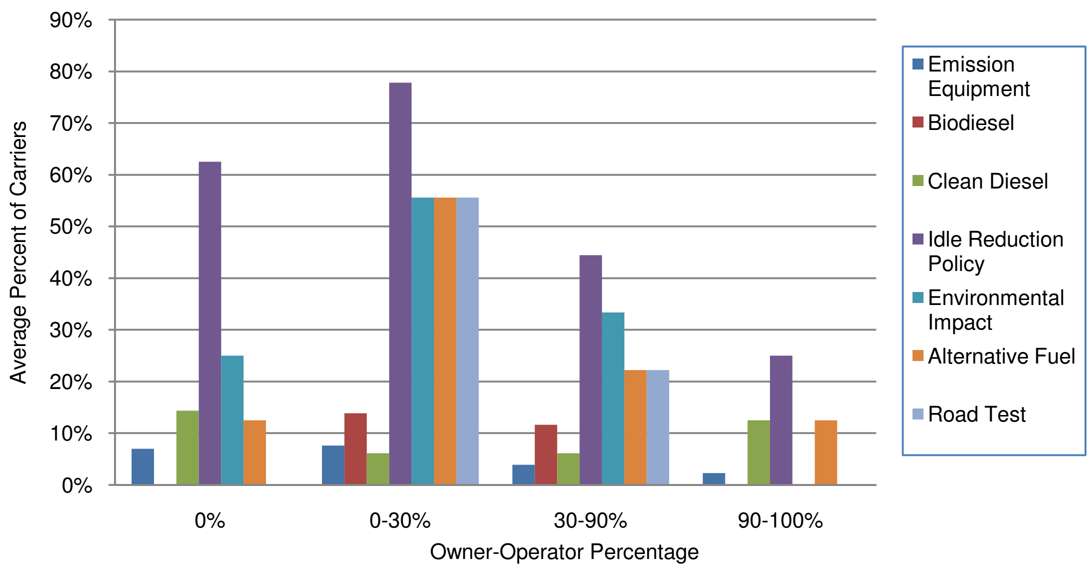


Figure 3.12 Programs and Policies versus Owner Operator Percentage

The 0-30 % owner operator percentage class has the highest percentage of idle reduction, environmental impact, alternative fuel programs as well as the highest percentage of alternative fuel road tests and biodiesel use. This subgroup also has a slightly higher percentage of vehicles equipped with emissions equipment. It is also important to note that carriers composed of more than 90% owner operators have the lowest percentages in almost every category which is consistent with expectations.

3.2.2 Short, Medium, or Long Haul

As described in previous sections, carrier business can be broken down into three main types of shipments; Short, Medium, and Long Haul. Carriers can range from those who specialize in one or two types of shipments, to those who are completely diversified. The purpose of this cross tabulation is to investigate the effects that the type of business may have on the vehicle classes a carrier uses, the emission equipment, and the fuel efficiency of the fleet. Carriers are placed into the Short, Medium, or Long Haul group depending upon which type of business they have the highest percentage.

3.2.2.1 Vehicle Class versus Business type

The average fleet composition for each group is shown in Figure 3.13. This cross tabulation indicates that Class 7 vehicles are used mostly for Short Hauls. This finding is consistent with expectations because these are the smallest capacity vehicles considered and would not be economical for long distances. Class 8 vehicles are used mostly for Medium Hauls and there is no clear trend for Class 9 vehicles. This data is useful for evaluating alternative technologies in the context of specific vehicle classes and shipment types. A technology for Class 7 vehicles, for example, would only be applicable on Short Haul shipments.

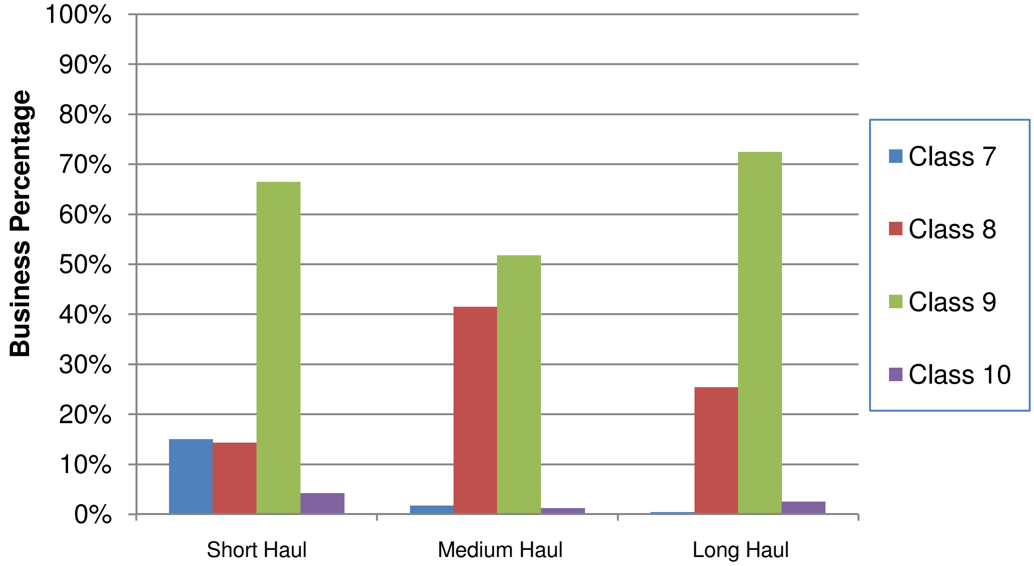


Figure 3.13 Vehicle Class versus Business Type

3.2.2.2 Emission Equipment versus Business type

The average percentage of vehicles with emissions equipment for each group is shown in Figure 3.14. This cross tabulation indicates that Long Haul shipments employ the greatest percentage of emissions equipment with the exception of automatic tire inflation. This is consistent with expectations because Long haul shipments will provide the best opportunity to recoup the investment in equipment due to high number of miles traveled. It also indicates that Short Haul shipments are not using a significant amount of emissions equipment which represents an opportunity for carriers to improve their environmental performance and increases their mpg by using an alternative fuel for technology.

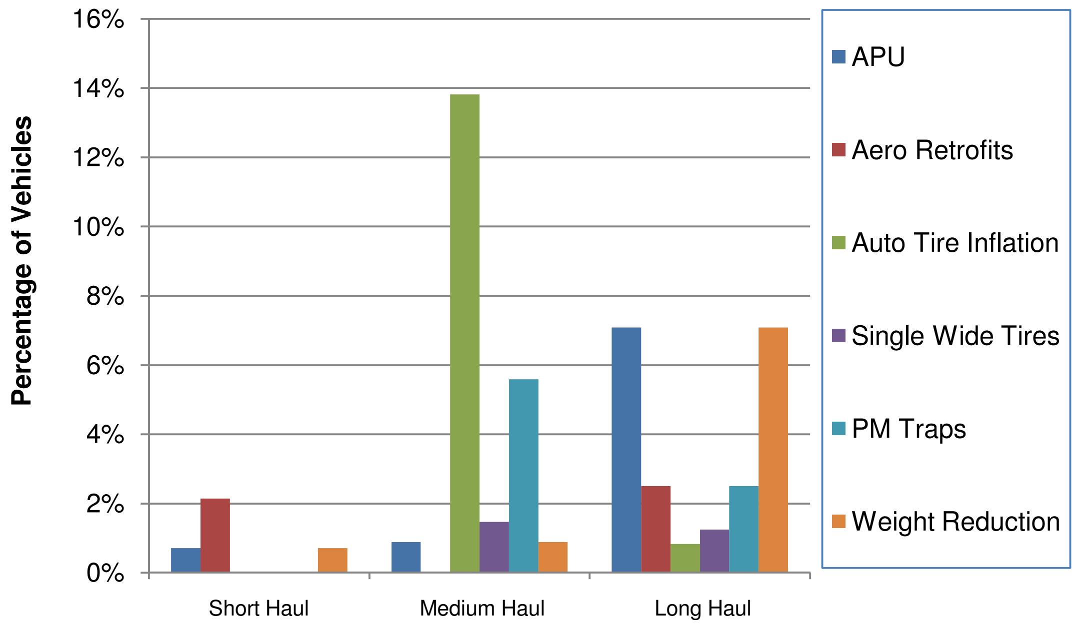


Figure 3.14 Emissions Equipment versus Business Type

3.2.2.3 Miles per Gallon versus Business type

The average miles per gallon for each group are shown in Figure 4.15. This cross tabulation indicates that carriers who have their highest business percentage as Medium Haul shipments also have the highest overall mpg across all categories. Another interesting trend is that carrier in who specialize in Long Haul shipment have a lower fuel mileage on long hauls when compared to carriers who specialize in Medium or Short Haul shipments. A similar trend exists for carriers who specialize in Short Haul shipments. It is expected that a carrier who specializes in a certain type of business should have a higher efficiency in that category, but this trend only occurs in the Medium Haul group.

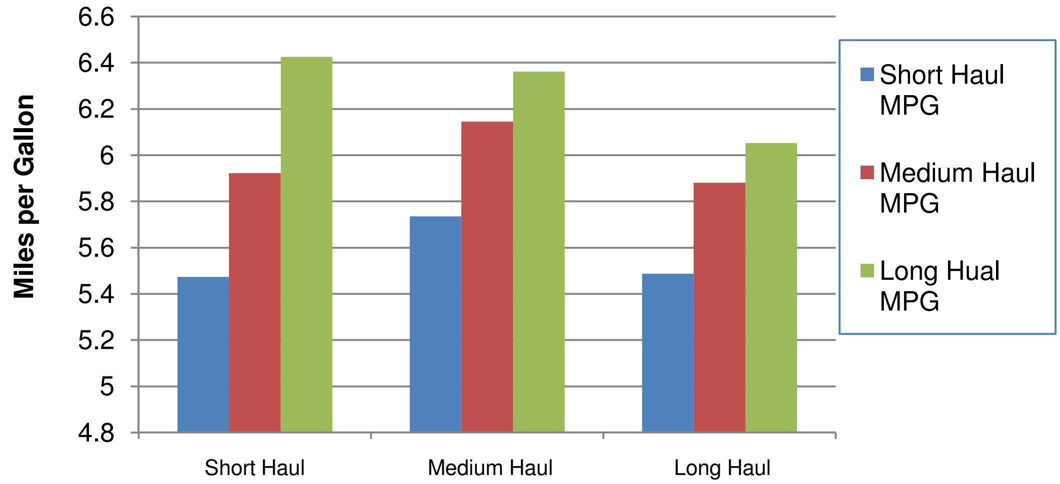


Figure 3.15 MPG versus Business Type

3.2.3 Vehicle Class

Some carriers specialize in a particular class of vehicles and some diversify. The purpose of this cross tabulation is to investigate the effect that vehicle class has on the type of business, average mpg, and programs of the carriers. The carriers are divided into two groups, those with a majority of class 8 vehicles and those with a majority of class 9 vehicles. Carriers with a majority class 7 and class 10 vehicles are not included in this division because they do not appear in significant numbers.

3.2.3.1 Business Type versus vehicle Class

The average percentage of Short, Medium, and Long Haul shipments for each group is shown in Figure 4.16. The lowest percentage of business is Short Haul, followed by Long Haul and then Medium Haul for each class of vehicle. Even though the composition of a carriers business is a good indicator of their fleet composition, as seen in section 4.2.2.1, the reverse may not necessarily be true because each class of vehicle follow the same trend.

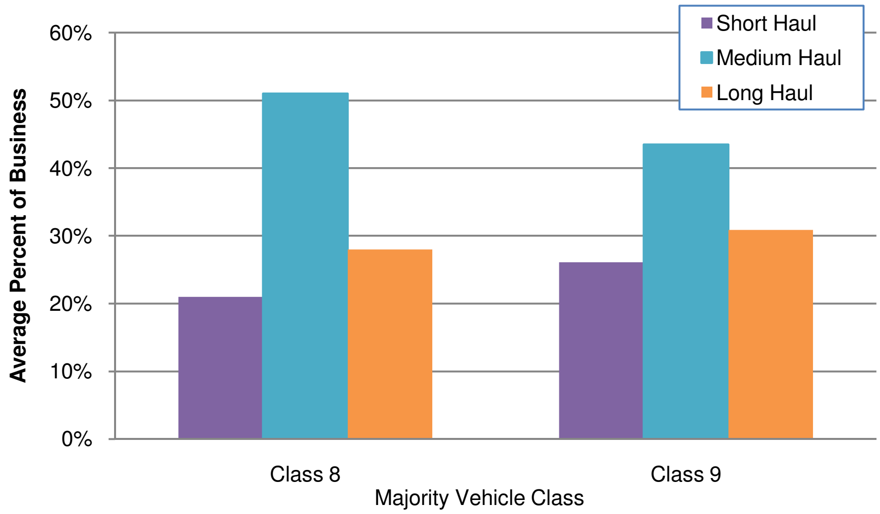


Figure 3.16 Average Business Type versus Vehicle Class

3.2.3.2Average MPG versus Vehicle Class

The average miles per gallon for the two groups are shown in Figure 4.17. This cross tabulation shows a drastic difference in the average mpg for Short Haul shipments between Class 8 and Class 9 vehicles. This supports the conclusion that Class 8 vehicles are best suited for Short Haul shipments. Class 9 vehicles had a higher mpg for Medium Haul and neither has a clear advantage for Long Haul shipments.

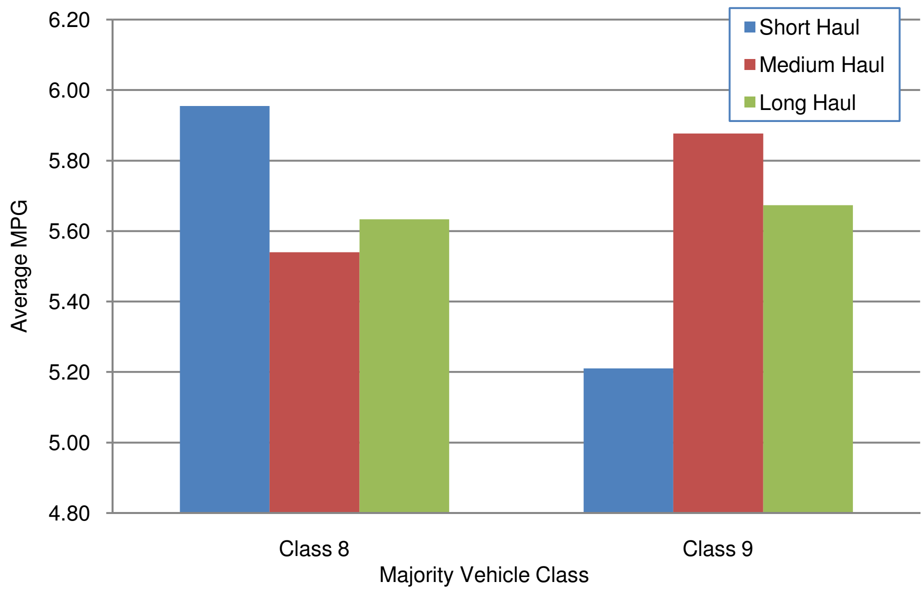


Figure 3.17 Average MPG versus Vehicle Class

3.2.3.3 Programs and Policies versus Vehicle Class

The average percentage of carriers using biodiesel, clean diesel technology, idle reduction policies, environmental impact programs, alternative fuel programs and road test are shown in Figure 4.18. The average owner operator percentage and average percent of vehicles equipped with emissions control technology is also shown in this figure. Carriers with majority of their fleet composed of Class 8 vehicles had higher percentages of idle reduction policies, environmental impact programs, alternative fuel programs, alternative fuel road tests, biodiesel use, and a higher percentage of vehicles equipped with emissions equipment. Carriers with a majority of Class 9 vehicles had a substantially higher percentage of owner operators, which may help explain these dramatic differences. The usage of idle reduction policies may help explain the difference in Short Haul fuel economy encountered in the previous section. Differences in emissions equipment and alternative fuel may be due to the lack of availability for Class 9 versus Class 8 vehicles.

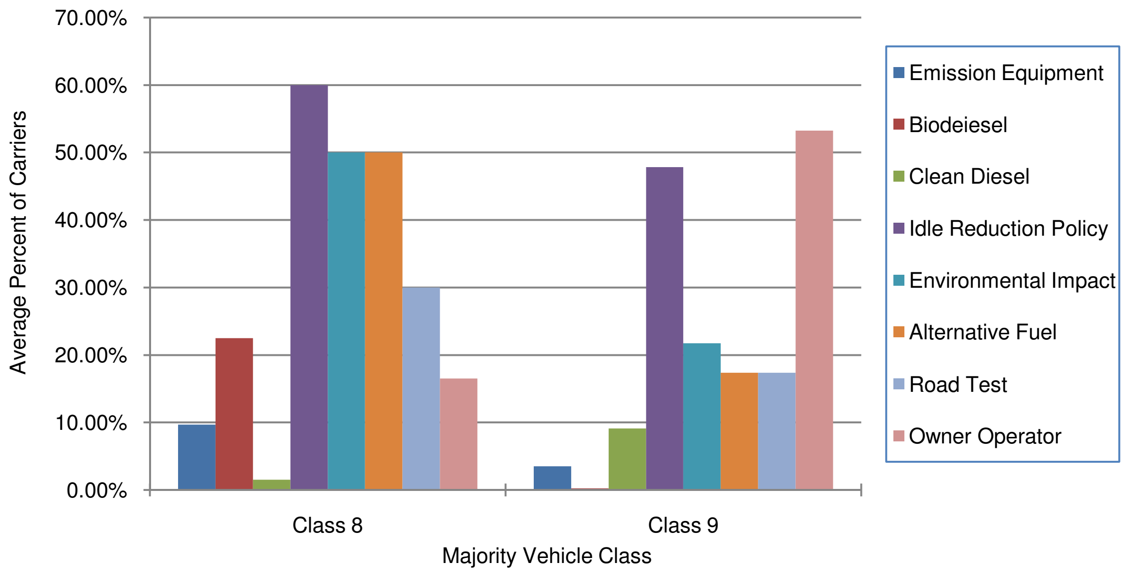


Figure 3.18 Programs and Policies versus Vehicle Class

3.2.4 Programs and Policies

The purpose of this cross tabulation is to determine if idle reduction, environmental impact, or alternative fuel programs have an impact on the average fuel economy of a carrier. The data shows that approximately 60% of carriers have idle reduction policies, 30% have environmental impact programs, and 30% have alternative fuel programs. The data also shows that 100% of carriers with environmental impact programs also have idle reduction policies and 70% of carriers with alternative fuel programs have environmental impact programs. It is therefore reasonable to assume that if a carrier has one program it is most likely an idle reduction policy. If they have two, it is an idle reduction policy and an environmental impact program and three programs imply they have an idle reduction policy, an environmental impact program and an alternative fuel program. Figure 4.19 shows the number of carriers versus the number of programs they have.

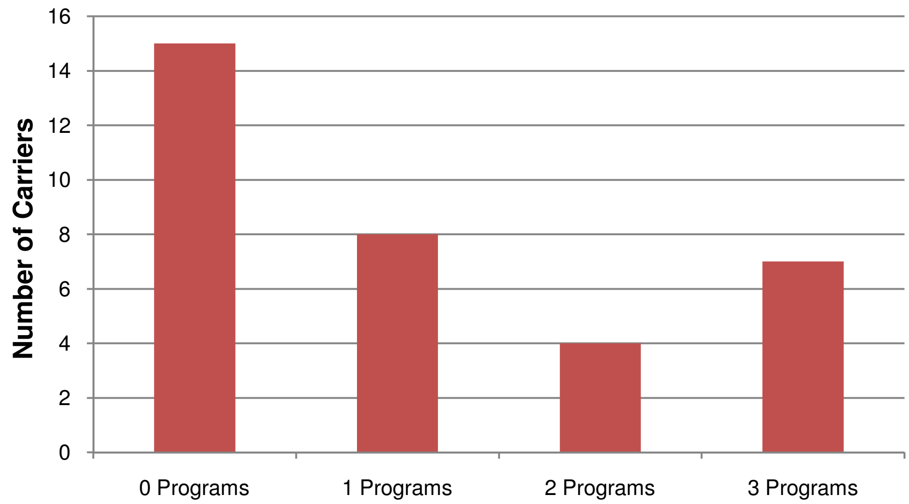


Figure 3.19 Alternative Fuel and Environmental Programs

It can be seen that the largest number of carriers have no programs at all, followed by carriers with only one program, then three and two. In order to evaluate the impact of these programs, the average mpg for the carriers is calculated and is shown in Figure 4.20.

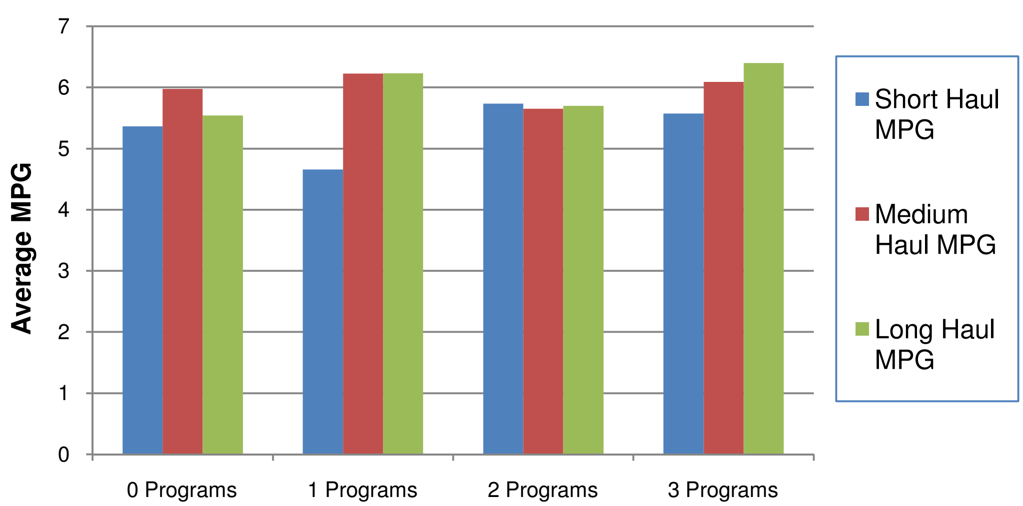


Figure 3.20 Programs versus Average MPG

Carriers with three programs have the best average mpg but those with two or three programs have no clear advantage over carriers without programs. This could be due to the use of emissions equipment, which can negatively impact mpg, but this does not explain why the Short Haul average mpg of carriers with an idle reduction policy is less than those without. The answer may be in the fact that these fuel economies are not weighted by percent of business type or possibly the owner operator percentage is affecting the results as described in previous sections. The Medium and Long haul fuel economies, however, do behave as expected.

3.3 Qualitative Results and Conclusions

It is clear from the survey results that most carriers are not using existing technologies which are designed to either increase efficiency or reduce their environmental impact. This provides an opportunity to implement these technologies on existing diesel platforms but also increases the benefits which would be gained from switching to an alternative fuel or technology which is innately cleaner or cost effective.

Class 7 or Class 10 vehicles are not viable for widespread implementation of alternative fuels or technology due to low fleet composition percentages while Class 8 and Class 9 vehicles are run in large numbers. Class 8 vehicles make the best candidates because many carriers specialize in them and would enjoy large economies of scale. Class 8 vehicles are also best suited for Shot Haul, which have the lowest mpg and therefore represent the best opportunity for alternative fuels. While class 8 vehicles have the highest level of emissions equipment use, Class 9 vehicles running short haul shipments have the lowest level. Replacing Class 9 vehicles which make Short Haul shipments with Class 8 vehicles running alternative fuel vehicles may be a viable option. The survey results can be used to identify suitable partners with high percentage of business in the target application.

CHAPTER 4 METHODOLGY FOR IDENTFYING TOP TBL CANDIDATES

The first step in identifying the top alternative fuel or technology is to model the decision situation for the application. The decision model is then decomposed into individual elements which are evaluated for each candidate, resulting in a decision matrix which provides the criteria for selecting top performers for further analysis. In order to identify the candidates which will produce the strongest TBL business case, the candidate alternative fuels and technologies are ranked according to their expected reduction in tailpipe emissions and energy cost. The formation of the decision model and resulting matrix is presented in section 4.1 and the economic and environmental indexes are presented in Section 4.2 .

4.1 Decision Model

This section will outline the steps that are taken to decompose the problem into individual decision elements. The objectives of the decision situation are elicited and then identified as fundamental objectives or means objectives. These objectives are then organized into a Fundamental Objectives Hierarchy and a Means-Objectives Network. Using the objective hierarchy and network, an influence diagram is created to identify and relate individual design decisions, measures of effectives, probable outcomes, and uncertainties.

4.1.1 Fundamental and Means Objectives

The typical reasons for operating HDDVs on an alternative fuel or technology include; reducing operating costs, reducing health hazards, increase energy independence, increasing sustainability, improving corporate image, and complying with government mandates. These objectives can be generalized into three fundamental objectives which are congruent with the desired TBL framework, specifically; to provide an economic benefit to the operator, to provide benefit to society, and to reduce the impact on the environment. The creation of a positive TBL business case for the use of alternative fuels and technology is, therefore, the most fundamental objective for this design decision. The objectives for this decision situation can be organized into the Fundamental Objective Hierarchy shown in Figure 4.1.

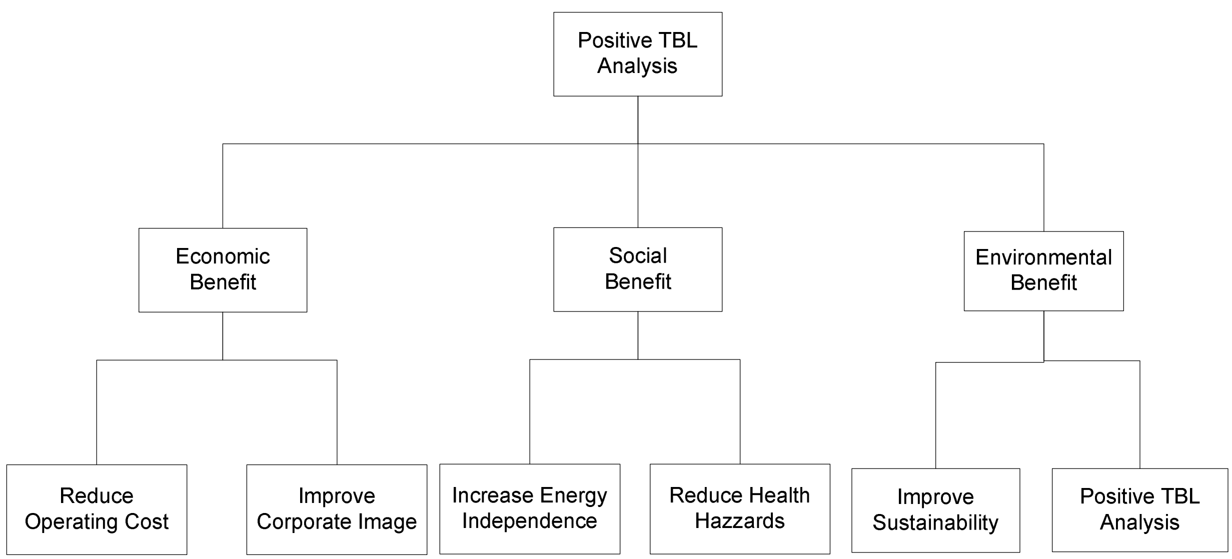


Figure 4.1 Fundamental Objectives Hierarchy

Means objectives are defined as objectives which are not of primary importance, but are relevant to the extent in which they impact fundamental objectives. These objectives are obtained by considering how the fundamental objectives can be achieved. It is possible for means objectives to impact multiple fundamental objectives, often in a conflicting manner. The formation of a Means Objectives Network, shown in Figure 3.2, aides in the evaluation of the potential impacts and design tradeoffs between the various objectives. It is important to note that an arrow indicates influence between two objectives, but does not imply whether or not that influence is positive or negative.

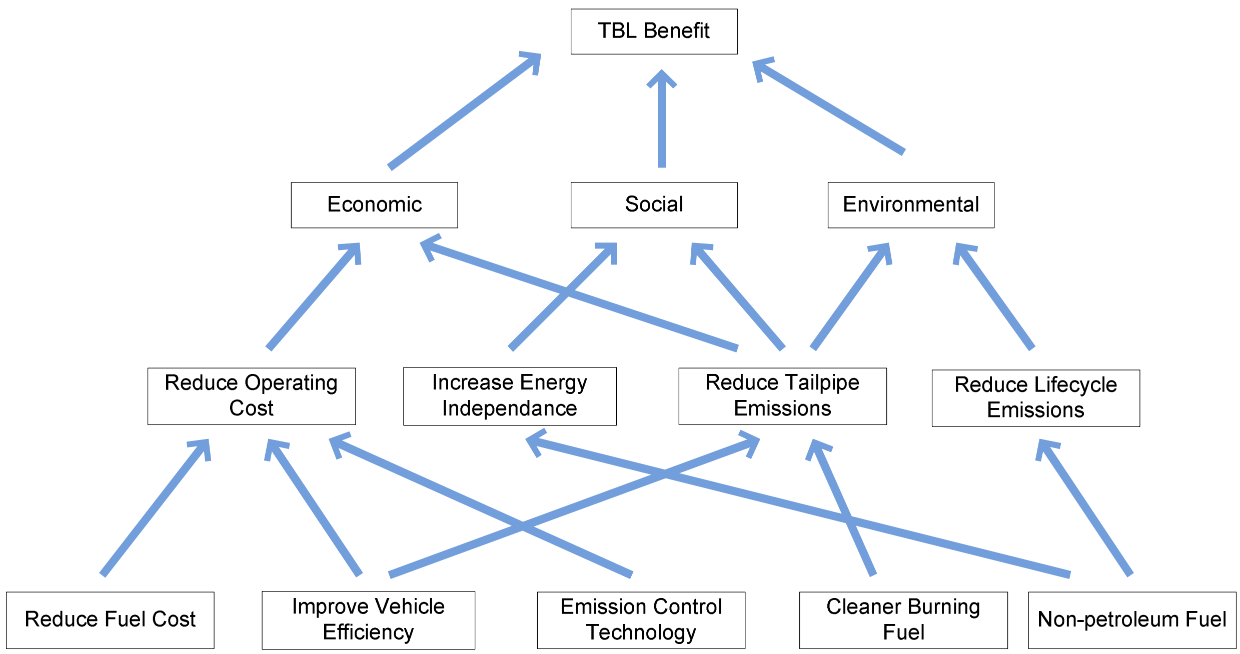


Figure 4.2 Means Objective Network

Means objective include; reducing operating cost, increasing energy Independence, reducing tailpipe emissions, reducing lifecycle emissions, reducing fuel costs, improving vehicle efficiency, cleaning emissions, burning fuel cleaner, and using non-petroleum based fuel. Reducing fuel costs is expected to impact operating costs. Improving vehicle efficiency is expected to impact operating costs and tailpipe emissions. Technology to clean emissions is expected to impact operating costs and tailpipe emissions. Burning Cleaner fuel is expected to impact tailpipe emissions and lifecycle emission. Using non-petroleum based fuels is expected to impact lifecycle emissions and energy independence. In order to evaluate these impacts, and influence diagram is necessary. The creation and explanation of the influence diagram is given in the following section.

4.1.2 Influence Diagram

An influence diagram, shown in Figure 3.3, indicates a relationship between the design decisions, intermediate outcomes, uncertain events, and the measures of effectiveness. Design decisions are fundamental variables which are controlled by a decision maker and are indicated with a box. Intermediate outcomes are calculations which are not of primary importance, but necessary to evaluate measures of effectiveness. Measures of effectiveness are calculations which are used as benchmarks for evaluating various design choices. Both intermediate outcomes and measures of effectiveness are indicated with a curved box. Uncertain events, indicated with an oval, are variables which the decision maker has no control over, vary unpredictably or are future events.

The TBL business analysis consists of four key decisions; the alternative fuel, alternative technology, facility investment, and vehicles investment. Intermediate outcomes include; incremental vehicle cost, change in fuel cost, change in vehicle efficiency, change in tailpipe emissions, carbon footprint, vehicle range, vehicle performance, equipment utilization, and operating costs. Uncertain events include the availability of fuels and technology, the price of diesel, taxes, government incentives and regulations. The measures of effectiveness are the economic, social, and environmental benefit.

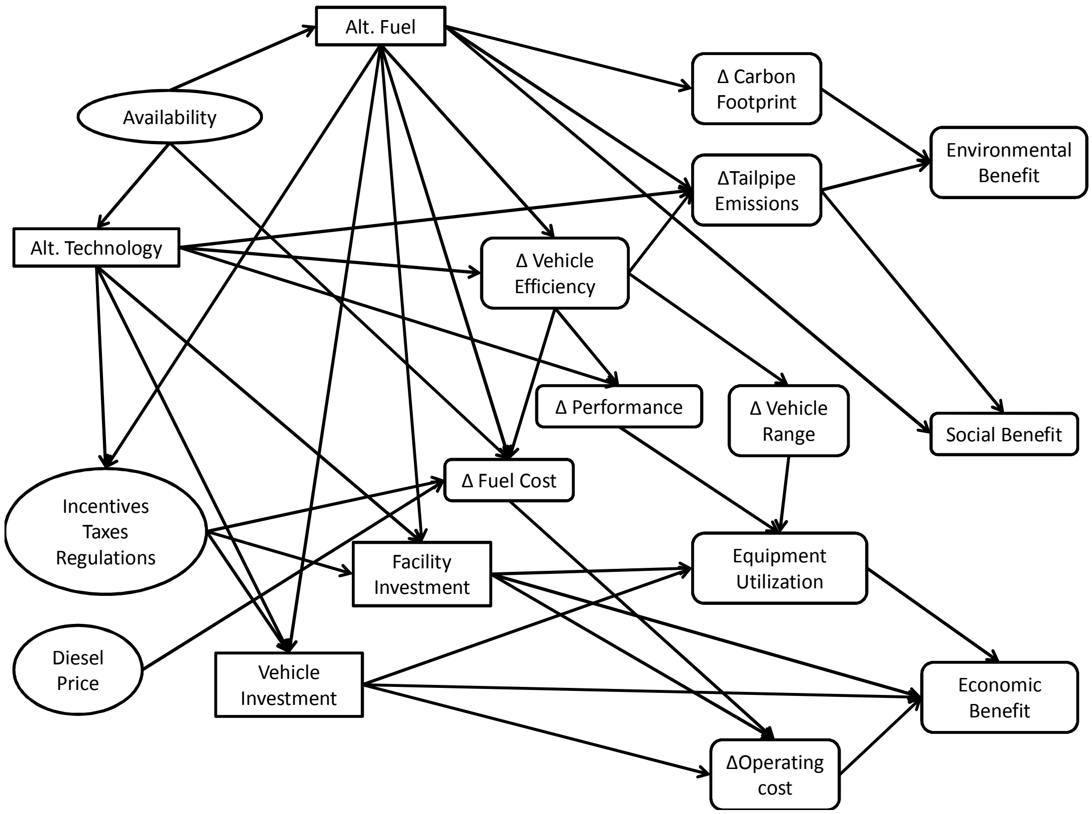


Figure 4.3 Influence Diagram

4.1.2.1 Design Decisions

The choice of alternative fuels is limited by availability. Different fuels can have different government taxes, regulations and incentives. Since each fuel can have dramatically different requirements to operate, the choice of alternative fuels affects the level of vehicle and facility investment which is required. Onsite CNG, for example, requires significant modifications to existing vehicles and may require special refueling equipment. The physical properties of the fuel will impact the efficiency of a HDDV. Fuels with lower cetane numbers, for example, must be run at lower compression ratios which results in lower vehicle efficiency. The physical properties of the fuel also affect the way they combust, thus impacting the exhaust emissions. Additionally, each fuel will have a different carbon footprint and cost.

Similar to alternative fuels, the choice of alternative technology is also limited by availability. Different technology and can have different government taxes, regulations and incentives. Alternative technologies have significant vehicle and facility investment. Battery – electric vehicles, for example, require sizeable investment in both the vehicle and recharging stations. Alternative technologies can have a positive or negative impact on the performance and efficiency of the vehicle. Hybrids, for example, increase the efficiency of the engine as well as maximum power available to propel the vehicle while exhaust after-treatments, such as particulate filters, are usually parasitic.

The level of vehicle and facility investment determines the operating cost, equipment utilization, and ultimately the economic benefit. It is important to note the equipment utilization is heavily influenced by other attributes such as vehicle range, performance, and efficiency. The social and environmental benefits, however, are primarily influenced by the change in tailpipe emissions and the carbon footprint.

4.1.3 Decision Matrix

The intermediate outcomes and measures of effectiveness, which are derived in the decision model, are evaluated for each candidate alternative fuel and technology using the data gathered during the literature review and carrier survey. The decision matrix for the large automotive manufacturer's application is shown in Table 7.

Table 7 Decision Matrix

Alt Fuel / Technology	Vehicle Investment	Facilitiy Investment	∆Fuel Cost	∆Efficiency	∆Vehicle Range	Performance	∆ Tailpipe Emissions	Gov Incentives	Availability
B-100	Low	None	↑	↓	-	↓	↓↓	yes	low
B-20	None	None	↑	-	-	-	|	yes	moderate
B-10	None	None	↑	-	-	-	↓	no	low
CNG - commercial	High	None	↑↑	↓	↓↓	↓	↓↓	yes	moderate
CNG -onsite	High	High	↓↓	↓	↓↓	↓	↓↓	yes	NA
ED-10	Low	None	↑	-	-	↓	↓	yes	moderate
E100	Med	None	↑	↓	-	↓	↓↓	yes	low
E85	Med	None	↑↑	↓	-	↓	↓	yes	high
Methanol	Med	Med	↑↑	↓	↓	↓	↓↓	no	low
LPG - commercial	Med	None	↑	-	↓	↓	↓↓	yes	high
LPG -onsite	Med	High	↓	-	↓	↓	↓↓	yes	NA
LNG	Med	HIgh	↓	↓	↓	↓	↓↓	yes	low
Diesel-Hydraullic	High	None	↓	↑	↑	↑	↓	yes	low
Diesel-Electric Hybrid	High	Med	↓	↑	↑	↑	↓	yes	low
Clean Diesel Technology	Low	None	↑	↓	-	-	↓	yes	high

4.1.3.1 Decision Marker Preferences and Requirements

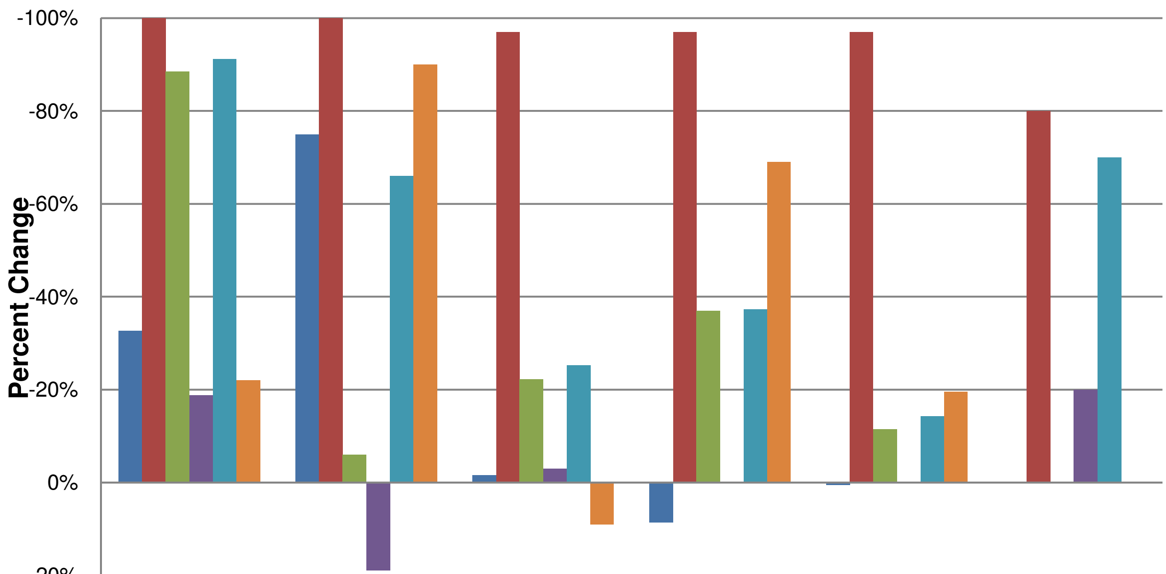
The preferences and requirements of the decision maker are used in conjunction with the decision matrix to eliminate candidates which could not possibly meet specifications. In the case of the large automotive manufacturer, the requirement that the candidate is available for implementation within two years is enough to reduce the number of candidates to a reasonable level. The large automotive manufacturer does, however, have a strong preference for candidates which have the potential to be economically positive. The remaining candidates for consideration are Propane, CNG, E-Diesel, B20 biodiesel, and Clean Diesel technology.

4.2 Social, Environmental, and Economic Index

An emissions index and an economic index are used to evaluate the remaining candidates under the assumption that candidates which rank higher in either index are more likely to produce a positive TBL business case. The emissions index for alternative fuels and technology is created using a percentage change in tailpipe emissions, for equal distance traveled, which is expected when switching the target application to an alternative fuel. The cost index for alternative fuels is created by relating the cost per MJ for the alternative fuel versus the standard diesel. The cost index serves is only a preliminary estimate of the expected change in fuel cost because it does not account for the changes in efficiency which may accompany an alternative fuel. The cost index for alternative technologies is based on the effectiveness of reducing emissions on a dollar per ton basis.

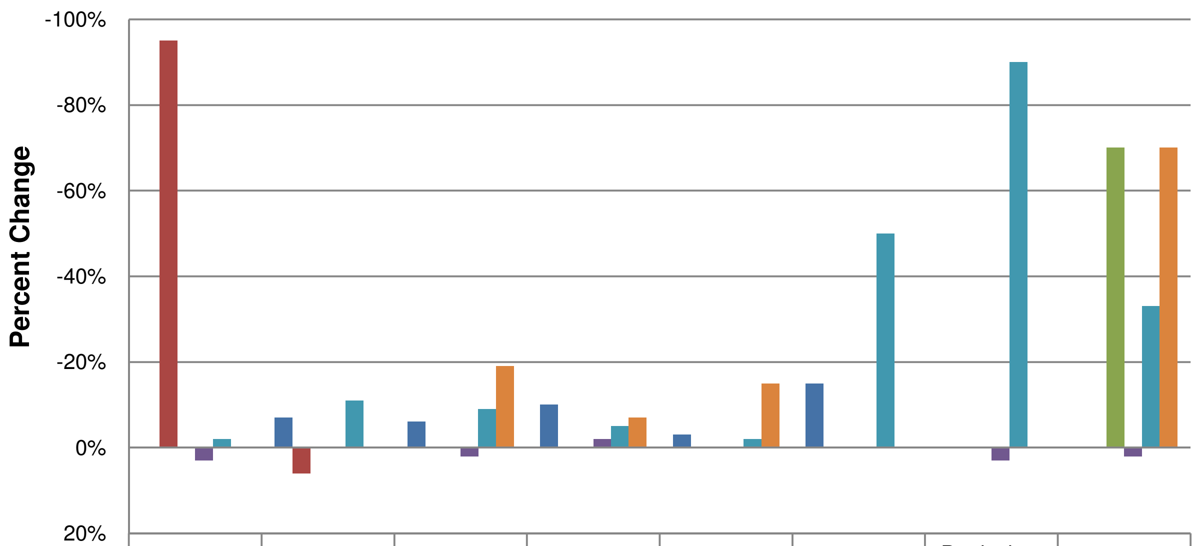
4.2.1 Expected Change in Tailpipe Emissions Index

The expected change in tailpipe emissions, versus standard diesel, for the remaining candidate fuels and technologies are tabulated in Figure 4.4 and Figure 4.5 . These values are taken from the literature survey, which is given in Chapter 2. Emissions data is gathered from several studies in which the emissions of diesel vehicles are studied before and after a switch to an alternative fuel. Studies testing the emissions of the target application on a chassis dynamometer running standard fuel and an alternative fuel or technology under standard drive cycles are preferred, but in some cases this was not available. Studies comparing emissions of vehicle in-use are used if dynamometer tests are not available and test utilizing transit buses are used if not tests using heavy duty trucks are available. It is important to note that measurements of exhaust pollutants on chassis dynamometers show considerable variation between similar vehicles that can mask small changes that might result from using a different fuels and technology. Emissions also vary according to engine condition and the accuracy of test cycles depend on the driver (Beer, et al., 2001). These inaccuracies are neglected because this index only serves as an approximation. In-use tests of the target application are required to accurately account for the emissions savings.



	Natural Gas	Methanol	E-Diesel (ED-10)	Biodiesel (B-100)	Biodiesel (B-20)	LPG
NOX	-33%	-75%	-2%	9%	1%	0%
SOX	-100%	-100%	-97%	-97%	-97%	-80%
CO	-89%	-6%	-22%	-37%	-12%	0%
CO2	-19%	19%	-3%	0%	0%	-20%
PM	-91%	-66%	-25%	-37%	-14%	-70%
NMHC	-22%	-90%	9%	-69%	-20%	0%

Figure 4.4 Percent Change in Tailpipe Emissions of Fuels versus Standard Diesel



	Low Sulfur	Low Density Diesel	CARB Diesel	Detergent Additive	Cetane Additives	Diesel-Water Emulsion	Particulate Matter Traps	Oxidation Catalyst
NOX	0%	-7%	-6%	-10%	-3%	-15%	0%	0%
SOX	-95%	6%	0%	0%	0%	0%	0%	0%
CO	0%	0%	0%	0%	0%	0%	0%	-70%
CO2	3%	0%	2%	-2%	0%	0%	3%	2%
PM	-2%	-11%	-9%	-5%	-2%	-50%	-90%	-33%
NMHC	0%	0%	-19%	-7%	-15%	0%	0%	-70%

Figure 4.5 Percent Change in Tailpipe Emissions of Clean Diesel versus Standard Diesel

The index of tailpipe emissions in this raw form is only useful for a qualitative assessment. A weighting scheme is used to sum the potential reductions and produce clear rankings. This weighting scheme is a function of the rate at which the target application emits the species and the relative impact that species has on society and the environment. The emissions rates and impacts of emissions are derived in detail in Chapter 5. The expected change in emissions is then normalized to hydrogen, which is assumed to reduce all tailpipe emissions to zero. The resulting index for the large automotive manufacturer's application is shown in Table 8.

Table 8 Expected Reduction in Impact Weighted Emissions for the Target Application

Rank	Emisisons / Technolgoy	Weighted Reduction in Tailpipe Emissions
	Hydrogen	100%
1	Methanol	67.9%
2	Natural Gas	46.8%
3	Diesel-Water Emulsion	18.6%
4	LPG	17.9%
5	Particulate Matter Traps	14.2%
6	E-Diesel (ED-10)	12.6%
7	Biodiesel (B-20)	9.3%
8	Detergent Additive	8.0%
9	Biodiesel (B-100)	7.4%
10	Low Sulfur Diesel	7.2%
11	Low Density Diesel	6.3%
12	Oxidation Catalyst	5.9%
13	CARB Diesel	5.7%
14	Cetane Additives	2.5%

4.2.2 Life-Cycle GHG Emissions Index

There are major areas of uncertainty, disagreement, and incompleteness in the existing literature regarding the lifecycle emissions of greenhouse gasses associated with alternative fuels and technologies. These areas include: treatment of lifecycle analyses within a dynamic economic-equilibrium framework, issues concerning energy use and emission factors, incorporation of the lifecycle of infrastructure and materials, representation of changes in land use, treatment of market impacts of co-products, development of CO_2 equivalency factors for all compounds, and detailed representation of the nitrogen cycle and its impacts (Delucchi, 2006). The lifecycle GHG emissions for various fuels also depend a great deal on the production path and feedstock used. The original concept for this method includes a provision for creating an index of GHG emissions, but until the lifecycle assessments are standardized and the production paths for better defined, such an index would not be useful.

4.2.3 Economic Impact Index

4.2.3.1 Alternative Fuels

The energy content, density, and cost for each of the candidate fuels are given Table 9. It is important to note that natural gas has two different prices because CNG can be purchased commercially or purchased from the utility company and compressed onsite. Pricing information is obtained from the literature review and by directly contacting vendors. Prices are valid as of July 2007 for the Michigan area.

Table 9 Fuel Properties and Average Costs – July 2007

Fuel	Density (g/mL)	LHV (MJ/kg)	Cost	Units
No.2 Diesel	0.850	43.0	2.96	$/galUS
B20	0.852	41.5	2.96	$/galUS
B100	0.860	37.1	3.31	$/galUS
ED10	0.85	41.0	2.91	$/galUS
NG- onsite	0.001	50.2	12.00	$/MCF
CNG	0.16	50.2	0.55	$/galUS
LPG	0.510	46.6	2.58	$/galUS
Diesel-Water	0.85	33.0	2.618	$/galUS
Detergent Additive	0.850	43.0	2.97	$/galUS
Cetane Improver	0.85	43.0	2.98	$/galUS
Low Density	0.831	43.0	3.01	$/galUS
CARB	0.837	43.0	3.12	$/galUS
Low Sulfur	0.848	43.0	3.08	$/galUS
Methanol	0.791	19.9	1.34	$/galUS

The economic index for fuels is based on the cost per megajoule, based on the lower heating value, to avoid the problems associated with the different volumetric energy densities of the fuels. This approach does not take into account the change in energy efficient which may be inherent with operating each fuel, but it still serves as a good approximation of the change in fuel cost which can be expected. The required capital investment, maintenance costs, and various other applications specific costs are not accounted for in this index and will be addressed when the TBL business model is created in Chapter 5. Figure 4.6 shows the cost of each of the candidate fuels on a dollar per megajoule basis.

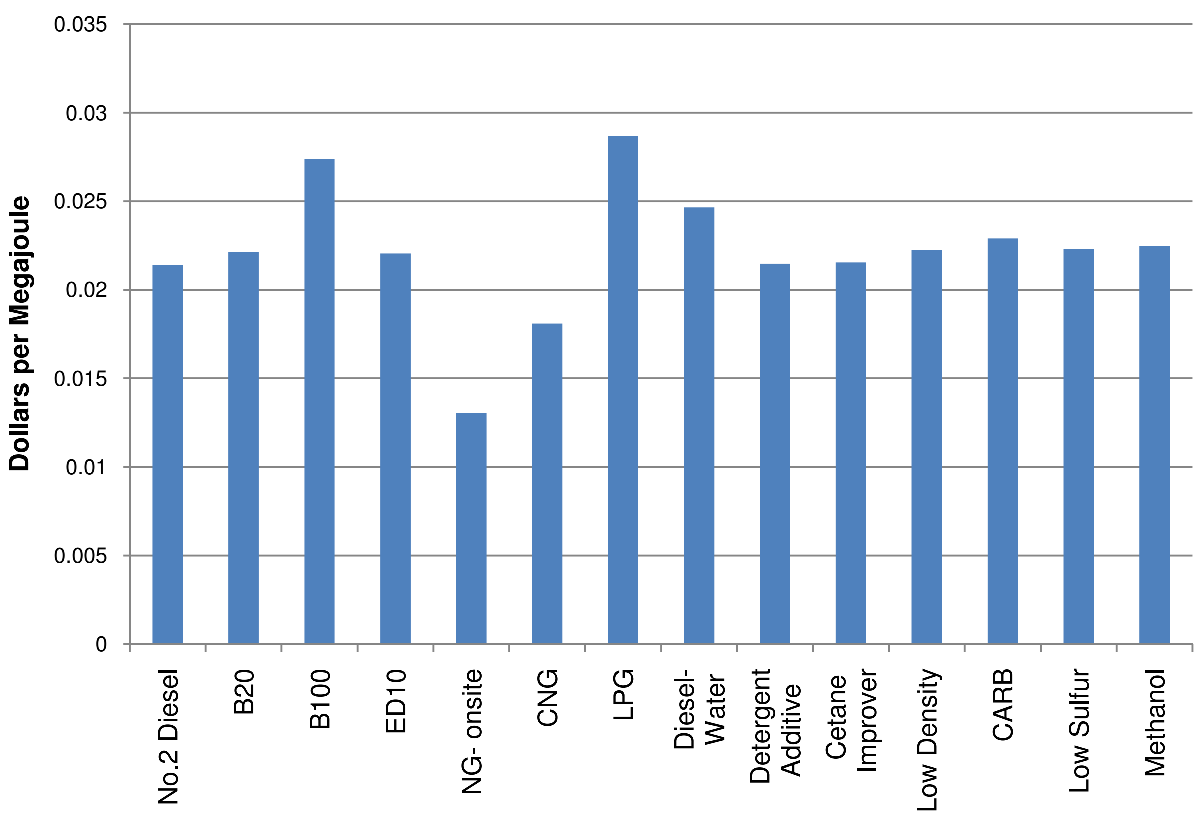


Figure 4.6 Energy Based Fuel Cost

These values are then normalized to standard diesel and organized into the fuel cost index shown in Table 10.

Table 10 Economic Index for Alternative Fuels

Rank	Density	Percent Change in Energy Cost versus Diesel
1	NG- onsite	-39.0%
2	CNG	-15.4%
3	Detergent Additive	0.3%
4	Cetane Improver	0.7%
5	ED10	3.0%
6	B20	3.4%
7	Low Density	4.0%
8	Low Sulfur	4.3%
9	Methanol	5.1%
10	CARB	7.0%
11	Diesel-Water	15.2%
12	B100	28.1%
13	LPG	34.0%

4.2.3.2 Alternative Technologies

An alternative technology cost index is necessary if there are several candidates which are viable. In this analysis, the only alternative technologies which were not eliminated from consideration are particulate filters and oxidation catalysts. This index is typically based on the change in operational cost per mile or the capital cost divided over useful life. Since both of these technologies are likely to be used in conjunction with any of the alternative fuels selected, an index is not necessary. The capital cost of these technologies is low, so it will be assumed that any alternative fuel which would benefit from using a particulate filter and/or an oxidation catalyst will do so.

4.2.4 Results and Conclusions

Natural gas, purchased from the utility company and compressed on-site, has an enormous cost advantage compared to standard diesel and any other alternative fuel. Natural gas also ranks second in the emissions index. Methanol ranks higher in the emissions index, but ranks very poorly in the economic index. Given the large automotive manufacturer's preference for an economically positive business case, on-site compressed natural gas is selected for the initial case study.

CHAPTER 5 EMISSIONS MOEDELING AND TBL FRAMEWORK

The TBL business case for implementing an alternative fuel or technology is based on the additional investment required for implementation and the expected change in operating costs versus standard diesel. The TBL analysis can therefore be viewed as the incremental business case for the addition of alternative fuel vehicles to an existing or planed truckload carrier business. This separation allows the costs and benefits of alternative fuel vehicles to be addressed independently from the business plan for operating the company. In order to build the TBL analysis, the emissions characteristics of the target application must be modeled and the change in operational costs, fuel costs, and emission rates must be calculated. It is then an iterative process to determine to determine the level of investment which will produce the strongest TBL business case. This chapter will outline the general steps necessary to build a TBL business case. The large automotive manufacturer s application is used as an example and a detailed analysis of the TBL business case for on-site CNG in the large automotive manufacturer's carrier network is presented in Chapter 6.

5.1 Emissions Modeling

It is necessary to characterize both the emission rate of the target application and the cost of emissions abatement. The emissions rates are estimated on a gram per mile basis using the EPA software Mobile6.2 and an approximated drive cycle for the target application. The value of emissions abatement is estimated on a dollar per ton rate for each type emission species based on a literature review which is shown in section 5.2.

5.1.1 Mobile 6.2

MOBILE6 is a computer program that estimates hydrocarbon, carbon monoxide, nitrogen oxide, particulate matter, sulfur oxides, ammonia, hazardous air pollutants, and carbon dioxide emission factors for gasoline-fueled and diesel motor vehicles. It is also used for certain specialized vehicles such as natural-gas-fueled or electric vehicles (United States Evironmental Protection Agency, August 2003).

MOBILE6 models are used by the EPA to evaluate mobile source control strategies. It is also used by states and regional planning agencies to develop emission inventories and control strategies for State Implementation Plans under the Clean Air Act and by state transportation departments for planning and conformity analysis. Academic and industry investigators also use MOBILE6 models to conduct research and develop environmental impact statements (United States Evironmental Protection Agency, August 2003). The following sections describe the necessary steps to create a MOBILE6 model for a specific application relating to the TBL analysis. The complete code used to model the large automotive manufacturer's application is given in Appendix A.

5.1.1.1 Input File Structure

All input files to MOBLE6 must be ASCII DOS text files. There are several types of inputs files to MOBILE6, but only the command file and external data files are necessary to model the emissions for the TBL analysis. Command input files allow users to specify what sorts of results are desired and to change input parameters while external data files are associated only with specific commands. The command input file consists of three distinct sections: The Header section, The Run section, and the Scenario section.

The Header section controls the overall input, output, and execution of the program. For the TBL analysis, the Header section is used to enable the output of NO_X, CO, CO_2, SO_X, and HC emission rates. Information supplied in the Header section will apply to all runs and scenarios described in the command input file. The RUN DATA command indicates the end of the Header section.

The Run section defines parameter values that customize the MOBILE6 runs. For the TBL analysis, the Run section is used to set the average temperature and to expand the reporting of emission factors. The information supplied in the Run section is specified once and applies to all scenarios in that run. The Run section begins with the RUN DATA command and ends with the first SCENARIO RECORD command. Although multiple Run sections are possible in a single command input file, only one is necessary for this analysis.

The Scenario section details the individual scenarios for which emission factors are calculated. Each MOBILE6 run can include many scenarios. Information supplied in the Scenario section is applied only to results only from that scenario. Each scenario begins with the SCENARIO RECORD command. The scenario section ends with either the next SCENARIO RECORD command or the END OF RUN command. Three scenarios are used in this TBL analysis to differentiate the emissions rates between short, medium, and long haul shipments.

5.1.1.2Vehicle Classification

Vehicle classes used in MOBILE6 do not match with those used in local vehicle registration systems or in reporting vehicle mileage data to the Federal Highway Administration’s , so care must be taken when relating vehicle types across these data source

(United States Evironmental Protection Agency, August 2003). Table 11 shows the vehicles classes which are of interest for this TBL analysis and abbreviations used by MOBILE6.

Table 11 Mobile 6 Vehicle Classifications

#	Abbreviation	Description
21	HDDV7	Class 7 Heavy-Duty Diesel Vehicles (26,001-33,000 lbs. GVWR)
22	HDDV8a	Class 8a Heavy-Duty Diesel Vehicles (33,001-60,000 lbs. GVWR)
23	HDDV8b	Class 8b Heavy-Duty Diesel Vehicles (>60,000 lbs. GVWR)

5.1.1.3 Input Parameters

MOBILE6 assigns default values for most of the data items that may appear in a MOBILE6 command input file. These most of these default values are acceptable for the TBL analysis and do not need to be altered. The following input parameters are necessary to model the specific application of interest; Calendar year, Hourly Temperature, Fuel characteristics, Registration age distribution by vehicle class, and Distribution of vehicle miles traveled by roadway type.

MOBILE6 uses the minimum and maximum daily temperatures to perform several calculations, such as temperature corrections to exhaust HC, CO, and NO_x, evaporative emissions, and refueling emissions. The minimum and maximum ambient temperatures must be specified, but the two values may be equal, indicating no temperature change occurred during the entire day. Since diesel fuel does not have significant evaporative or refueling emissions and the effect of temperature is not of general concern, the temperature is set a constant value of 60°F (United States Environmental Protection Agency, August 2003).

MOBILE6 requires an input for the Low Reid Vapor Pressure, RVP, of gasoline. Exhaust and especially non-exhaust emissions vary with fuel volatility. The RVP value entered must reflect the average in-use RVP of gasoline in the region of the country being modeled. The RVP value can be between 6.5 psi and 15.2 psi, inclusive. Since this parameter will have no impact on diesel emissions, a nominal value of 9 psi is selected. The registration age, and distribution of vehicle miles traveled by roadway type, however, require special consideration and are discussed in the subsequent sections.

5.1.1.4 Fractions of Vehicle Miles Traveled (VMT)

The VMT BY FACILITY command allows users to enter vehicle miles traveled (VMT) distributions for each of the 28 vehicle classes across four roadway types for each of the 24 hours of the day. This data must be entered in an external data file which contains the VMT BY FACILITY command name in the first column of the first row. The vehicle class numbers and the 96 VMT fractions representing the fraction of travel on each roadway type at each hour of the day for that vehicle class. The user is permitted to enter VMT fractions individual vehicle class, or for any number of vehicle classes up to 28 classes. The user supplies percentages of travel time for each hour of the day which represents highway, arterial roads, local roads, and ramps. The distributions for each hour must add up to 1, if they do not, MOBILE6 will automatically normalize them (United States Environmental Protection Agency, August 2003). For this analysis it is assumed that long haul shipment will have a higher percentage of their time spent on the highway and that short haul shipments will have a higher percentage of their time spent on arterial and local roads. Default values are used for the medium haul shipment.

5.1.1.5 Distribution of Vehicle Registrations

This command allows users to supply vehicle registration distributions by vehicle age for any of the vehicle types. By default, MOBILE6 applies a registration distribution based on U.S. vehicle fleet data. An external data file is necessary to input the distribution of vehicle registrations. The user must specify a percentage of vehicles in use for of for each of the past 25 years. A percentage of 10% for year 10, for example, would indicate that 10% of the vehicles in the simulation are ten years old. For this analysis, the vehicle distribution is set to only include the newest vehicles to represent an accurate baseline for comparing a new diesel vehicle versus and alternative.

5.1.1.6 Model Output - Emissions

MOBILE6 basic emission rates are derived from emissions tests conducted under standard conditions such as temperature, fuel, and driving cycle. (United States Evironmental Protection Agency, August 2003). The EPA has gone to great lengths to assure that MOBILE6 is based on the best data and calculation methodologies available. EPA staff has produced more than 40 technical reports explaining the data analysis behind the MOBILE6 estimates and the methods used in the model.

MOBILE6 includes the ability to estimate CO_2 emissions. These emissions are estimated based on fuel economy performance estimates built into the model or supplied by the user. Unlike most other MOBILE6 emission estimates, these CO_2 emission estimates are not adjusted for speed, temperature, fuel content, or the effects of vehicle inspection maintenance programs. This means that MOBILE6 cannot be used to model the effects on CO_2 emissions by varying these parameters. It also means that these CO_2 emission estimates should only be used to model time periods which are large enough to reasonably assume that variation in these parameters does not have a significant net effect (United States Evironmental Protection Agency, August 2003).

The gram per mile emissions rates obtained from the MOBILE6 model for this TBL analysis is shown in Table 12. Results are included for three vehicles class and three shipment types. The MOBILE6 code for this simulation is given in Appendix A.

Table 12 Gram per Mile Emission Rates for HDDV

Pollutant	HDDV7			HDDV8a			HDDV8b		
	Short	Medium	Long	Short	Medium	Long	Short	Medium	Long
Sulfur Oxides	0.270	0.270	0.270	0.308	0.308	0.308	0.322	0.322	0.322
Total Hydrocarbons	0.306	0.306	0.257	0.496	0.318	0.266	0.559	0.358	0.300
Carbon Monoxide	1.552	1.601	1.408	3.842	2.276	2.001	4.293	2.543	2.236
Nitrogen Oxides	5.132	5.417	5.999	6.531	5.976	6.618	7.223	6.610	7.320
Carbon Dioxide	1,352	1,352	1,352	1,544	1,544	1,544	1,615	1,616	1,615
Particulate Matter	0.193	0.193	0.193	0.273	0.273	0.273	0.272	0.272	0.272

5.1.1.7 Natural Gas Vehicles in MOBILE6

Since natural gas is top performing candidate, the capability of MOBILE6 to model CNG emissions is investigated. The NGV FRACTION command specifies the percent of NGVs in each of the vehicle classes. If 100% is entered, MOBILE6 will report the basic NGV emission rate. Any other percentage will specify a fleet that is part NGV, with gasoline and diesel vehicles comprising the remaining part of the fleet. The NGV FRACTION command also affects evaporative emissions for gasoline vehicles, which MOBILE6 assumes are zero for NGVs. For this analysis, the natural gas fraction is set to 100% for the vehicles classes of interest and the results are shown in Table 13. The percent reduction versus the standard case is shown in Table 14. The CNG emissions reductions predicted by MOBILE6 are less than those found in the literature review, most likely because the CNG modeling ability of MOBILE6 is limited and does not include recent advances in CNG technology and the use of three-way catalysts. It is important to note the total hydrocarbons can increase several fold.

Table 13 Gram per Mile Emissions for NGV

Pollutant	HDDV7			HDDV8a			HDDV8b		
	Short	Medium	Long	Short	Medium	Long	Short	Medium	Long
Sulfur Oxides	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total Hydrocarbons	13.382	13.391	11.226	17.667	11.313	9.484	19.827	12.696	10.643
Carbon Monoxide	0.624	0.644	0.566	1.555	0.921	0.810	1.746	1.034	0.909
Nitrogen Oxides	4.497	4.747	5.257	6.053	5.539	6.134	6.697	6.129	6.787
Particulate Matter	0.175	0.175	0.175	0.253	0.253	0.253	0.251	0.251	0.251

Table 14 Percent Reduction in Tailpipe Emissions Estimated by MOBLE6

Pollutant	HDDV7	HDDV8a	HDDV8b
Sulfur Oxides	-100%	-100%	-100%
Total Hydrocarbons	427%	346%	344%
Carbon Monoxide	-60%	-60%	-59%
Nitrogen Oxides	-12%	-7%	-7%
Particulate Matter	-9%	-7%	-8%

5.1.2 Dollar Value of Emissions Abatement

Emissions abatement refers to a technology used, or measures taken, to reduce pollution. It also refers to measures taken to reduce the impact of emissions on health or the environment. Estimated unit costs of emissions vary widely because of the difficulties and differences in assessing their social, environmental, and health impacts as well as the use of a variety of types of control techniques (Hsiaotao T. Bi, 2006). Dollar values are typically estimated based on damage costs or control costs. Damage cost valuation involves estimating the actual value of the harm caused by vehicle emissions, whereas control cost valuation examines the cost of the measures necessary to reduce air pollutant emission. Damage cost valuation is preferable because studies that use control costs to value air pollution rely on the assumption that the controls placed on pollution are efficient (Booz-Allen & Hamilton Inc., 1999).

5.1.2.1Environmental Assessment

The largest impact of emissions on the environment is air quality and the relationship between emissions and air quantity is non-linear for some pollutants. For pollutants which are directly emitted, such as carbon monoxide, the change in air pollution concentration can be considered proportional to emissions. For secondary pollutants, such as ozone, the relationship is more difficult to estimate. Some of the factors that can influence changes in air quality are the ratio between volatile organic compound and nitrogen oxides. If the ratio of ambient levels of VOC to NO_x is high, ozone formation is limited by nitrogen oxides and if this ratio is low, ozone formation is limited by volatile organic compounds. In either case, reducing the non-limiting pollutant has little effect on overall ozone formation (Booz-Allen & Hamilton Inc., 1999). Climate and meteorological conditions such as temperature, sunlight, and wind, have a large impact on ambient air quality. The Los Angeles air basin, for example, is particularly susceptible to air pollution problems because high temperatures, lots of sunlight, and low winds tend to increase ozone formation (Booz-Allen & Hamilton Inc., 1999).

Methods for estimating environmental damage costs include studies in which people are directly asked how much money they would be willing to pay for a certain improvement, such as improved visibility via reduced smog. Using expressed preferences is a controversial approach to quantifying impacts, but is often used in policy analysis. One problem is that people may tailor their answers to affect policy or they may not completely understand the impact as described in the survey. People might be willing to spend more if they really understood the implications of the policy decision in question, or spend a great deal less if they had to pay for the policy out of pocket (Booz-Allen & Hamilton Inc., 1999). The results of several studies for the dollar value per ton of volatile organic compounds and nitrous oxides are shown in Table 15 and Table 16 respectively.

Table 15 Dollar Value of Emission Abatement for Volatile Organic Compounds

Volitile Organic Compounds/Hydrocarbon (VOC, HC)				
Value	**Units**	**Year**	**Source**	**Present Day Value (2007 real USD/ ton)**
749	$/ton	1999	Booz-Allen & Hamilton	957.72
954	$/ton	1999	Booz-Allen & Hamilton	1,219.85
2000	CAN$/ton	2001	IBI Group	2,404.91
9800	$/ton	1997	Johansson	13,325.19
4798	$/ton	1999	Walsh	6,135.05
2441	$/ton	1993	Hartman	3,753.13

Table 16 Dollar Value of Emission Abatement for Nitrous Oxides

Nitrous Oxides (NO_X)				
Value	**Units**	**Year**	**Source**	**Present Day Value (2007 real USD/ ton)**
10,144.00	$/ton	1999	Booz-Allen & Hamilton	12,970.81
11,646.00	$/ton	1999	Booz-Allen & Hamilton	14,891.37
2,000.00	CAN$/ton	2001	IBI Group	2,404.91
13,300.00	$/ton	1997	Johansson	18,084.19
18,255.00	$/ton	1999	Walsh	23,342.09
1,155.00	$/ton	1993	Hartman	1,775.86
10,650.00	$/ton	1991	Contadini	17,412.67

<u>*5.1.2.2 Health Assessment*</u>

The monetary value of health damage is not easy to assess. There are a number of factors that affect the dollar value of physical impairment, mortality, or other pollution damage. In particular, the severity of the damage, if the illness is chronic or temporary, and the age of persons affected influence the value of the damage. For agriculture damage, the value of crops is used as the value of damage (Booz-Allen & Hamilton Inc., 1999). The value of reducing mortality and morbidity is often estimated as to what society in general is willing to pay for such health improvements (Edwards, et al., 2005). Other quantifying methods include estimating health costs via increased hospital visits, medical procedures, prescription drug costs, and lost wages.

Human exposure to air pollution is also a factor in the value of health effects since more exposure to pollution will result in more health problems. Thus, the value of a ton of pollution in an urban area will tend to be greater than in a rural area because of greater population exposure. Some pollutants, like CO, tend to have localized impacts, while others are regional in scope. The results of several studies for the dollar value per ton of carbon monoxide, particulate matter and sulfur oxides are shown in Table 17, Table 18, and Table 19 respectively.

Table 17 Dollar Value of Emission Abatement for Carbon Monoxide

Carbon Monoxide (CO)				
Value	**Units**	**Year**	**Source**	**Present Day Value (2007 real USD/ ton)**
54.00	$/ton	1999	Booz-Allen & Hamilton	69.05
60.00	$/ton	1999	Booz-Allen & Hamilton	76.72
729.00	$/ton	1999	Walsh	932.15
1155.00	$/ton	1993	Hartman	1775.86
60.00	$/ton	1991	Contadini	98.10

Table 18 Dollar Value of Emission Abatement for Particulate Matter

Particulate Matter (PM)				
Value	**Units**	**Year**	**Source**	**Present Day Value (2007 real USD/ ton)**
78618	$/ton	1999	Booz-Allen & Hamilton	100,526.34
110258	$/ton	1999	Booz-Allen & Hamilton	140,983.40

Table 19 Dollar Value of Emission Abatement for Sulfur Oxides

Sulfur Oxides (SOX)				
Value	**Units**	**Year**	**Source**	**Present Day Value (2007 real USD/ ton)**
39732	$/ton	1999	Booz-Allen & Hamilton	50,804.05
55069	$/ton	1999	Booz-Allen & Hamilton	70,414.98

5.1.2.3 Damage Cost of GHG

Information on the effects of greenhouse gases is currently insufficient to support a meaningful range of damage cost estimates (Booz-Allen & Hamilton Inc., 1999). There is however, a very active market for purchasing offset credits for carbon emissions which represent the cost to control emissions. Values from various carbon offset providers are shown in Table 20.

Table 20 Dollar Value for Carbon Credits

Carbon Dioxide (CO_2)				
Value	**Units**	**Year**	**Source**	**website**
14.28	$/ton	2007	AtmosClear Climate Club	http://www.atmosclear.org/
4.90	$/ton	2007	Carbonfund.org	http://carbonfund.org
5.00	$/ton	2007	e-BlueHorizons	http://www.e-bluehorizons.com/
6.93	$/ton	2007	DriveNeutral.org	http://www.liveneutral.org/
9.18	$/ton	2007	Terrapass	http://www.terrapass.com/
13.20	$/ton	2007	Native Energy	http://www.nativeenergy.com/
16.00	$/ton	2007	The CarbonNeutral Company	http://www.carbonneutral.com/
17.50	$/ton	2007	Climate Friendly	https://climatefriendly.com/
18.00	$/ton	2007	Sustainable travel International	http://www.sustainabletravelinternational.org/
19.45	$/ton	2007	Uncook the Planet	http://www.uncook.com/
29.00	$/ton	2007	Bonneville Environmental Foundation	http://www.b-e-f.org/
30.00	$/ton	2007	Myclimate	http://www.myclimate.org/?lang=en

5.1.2.4 Emissions Abatement Values Used in TBL Analysis

The dollar value for emission abatement used in the TBL analysis is the average of the values found in the literature review. These values are shown in Table 21 along with the standard deviation.

Table 21 Estimated Dollar Value of Emission Abatement

Pollutant	Average Value	Std. Deviation	Units
Nitrogen oxides (NOX)	14,746.16	7,260.09	$/ton
Sulfur oxides (SOX)	60,609.51	13,867.03	$/ton
Carbon monoxide (CO)	590.38	758.31	$/ton
Carbon Dioxide	15.29	8.32	$/ton
Fine Particulates (PM)	120,754.87	28,607.46	$/ton
Volatile organic compounds (VOC, HC)	954.00	5,068.30	$/ton

5.2 Steps for creation of a TBL Business Case

The general steps for creating an incremental TBL business case for an alternative fuel or technology are listed below. The details of each step will vary depending on the nature and requirements of the alternative fuel or technology which is chosen. The analysis of On-site CNG in the next chapter will provide a more detailed explanation of what is required in each step.

1. Determine the facility requirements. This includes a refueling station, if necessary, or any special equipment necessary to service and operate an alternative fuel or technology. Information is obtained via literature review and direct supplier contact
2. Obtain pricing information on any necessary facilities via direct supplier contact
3. Calculate the cost of operating, maintaining, and insuring any facilities
4. Calculate the necessary tax implications associated with the facilities. This includes any increase in property taxes associated with the facility and tax credits which may be offered by government agencies
5. Determine the vehicle requirements, limitations, and performance.
6. Calculate the incremental vehicle cost for a HDDV operating the alternative fuel or technology compared to a conventional diesel powered vehicle
7. Calculate the change in operational cost on a per vehicle basis
8. Calculate the change in fuel costs on a per mile basis
9. Calculate the necessary tax implications on a per vehicle basis
10. Model the emissions characteristics of the target application
11. Estimate the expected reduction in tailpipe emissions for the target application on a per mile basis
12. Calculate the value of emissions abatement on a per mile basis
13. Identify suitable lanes for the target application
14. Calculate the number of vehicles which can be supported by a certain level of facility investment if applicable.
15. Determine the minimum capital investment required to implement the alternative fuel or technology.
16. Determine the number of miles which can be supported by the minimum level of capital investment in vehicles and/or facilities.
17. Calculate all revenue streams and costs on a yearly basis

18. Determine the simple payback period
19. Vary the level of facility and vehicle investment to obtain the quickest payback period
20. Determine the net present value and internal rate of return for the incremental TBL business case

5.3 Emissions Modeling Conclusions

MOBILE6 models can be used estimate hydrocarbon, carbon monoxide, nitrogen oxide, particulate matter, sulfur oxides, and carbon dioxide emission factors the target application. MOBILE6 models are used by the EPA to evaluate mobile source control strategies. Academic and industry investigators also use MOBILE6 models to conduct research and develop environmental impact statements. Most of the default input parameters can be used to produce useful results for the TBL analysis. Estimated unit costs of emissions vary widely because of the difficulties and differences in assessing their social, environmental, and health impacts as well as the use of a variety of types of control techniques. Dollar values are typically estimated based on damage costs or control costs. Damage cost valuation involves estimating the actual value of the harm caused by vehicle emissions, whereas control cost valuation examines the cost of the measures necessary to reduce air pollutant emission. Damage cost valuation is preferable because studies that use control costs to value air pollution rely on the assumption that the controls placed on pollution are efficient. The wide variation in costs suggests that further study is needed. Ideally, these dollar values would replaced with the market value of emissions in a cap and trade scenario.

CHAPTER 6 ONSITE COMPRESSED NATURAL GAS

6.1 Onsite CNG Facility

Natural gas must be compressed to between 3000 - 3,600 psi to provide adequate vehicle range at reasonable vehicle tank sizes. Refueling stations consist of multi-stage gas compressors with either electric or engine drives (EA Engineering, Science, and Technolgy, Inc., 1997). The outlet gas quality must meet the SAE J1616 specification for CNG motor fuel. There are two basic types of CNG refueling stations: slow-fill and fast-fill. Slow-fill CNG stations compress natural gas from a pipeline directly into the vehicles on-board storage tank. Depending on the flow rate of the compressor and the size of vehicle storage, it can take between 1 and 14 hours to fill the tank. Long refueling time makes this method more suitable for fleets in which are not in use for extended periods of times. The fast-fill method uses high-pressure ground storage tanks to serve as an intermediary which reduces the time the vehicles spends refueling. Although the fast-fill method does not reduce the compressor time to produce a gallon of CNG, it does reduce the refueling time from the vehicle's perspective. Refueling time for Fast-Fill systems is approximately 5 minutes, which is equivalent to conventional diesel refueling (United States Department of Energy). A Fast-Fill system, however, requires signicantly more capital investment.

The large automotive manufacturer's logistics network sends and recieves shipments almost 24 hours a day and these shipments are time sensitive due to lean manufacturing principles. Since there are no extended periods of inactivity and extended reueling time increases the risk of late shipments, a Fast-Fill refueling station is a necessuty for this application. The major component of a fast fill system are the compressor, ground storage tanks, dispensers, sequencer and filter. A description of each component is provided for each component in the following sections along with all relevant calculations.

6.1.1 Compressor

Compression is typically accomplished with four stage reciprocating compressors which have pressurized oil systems and are driven by three phase 208 volt or single phase 240 volt explosion proof motors. Systems are also equipped with fault conditions for low and high inlet pressure, low oil pressure, high motor temp, high discharge temperature, and low oil level. All the electrical components are required to meet National Fire Protection Association (NFPA) code 30a, 52, 54 and 70. The following sections present the relevant calculations for the compressor capacity, compressor costs, compressor work, and the cost to operate the compressor.

6.1.1.1 Compressor Capacity

The outlet flow rate of a compressor is rated in standard cubic feet per min, $scfm$. This flow rate determines the maximum volume of CNG which can be produced in a given time frame. The calculations in this section are used to determine the maximum number of CNG gallons which can be produced in one day. This metric is important because increasing the compressor capacity will increase the output of the refueling station but will also raise the capital costs.

It is assumed that natural gas is delivered to the compressor at standard temperature and pressure, which corresponds to a natural gas density, ρ_{NG}, of 0.6472 kg/m^3. Equation 1 is used to compute the mass flow rate of the compressor, $\dot{m}_{comp}$ and the maximum number of gallons per day that the compressor can produce, is calculated using Equation 2. The outlet conditions of the compressor are assumed to be 25℃ and 24,820 kPa (3,600 psi) which corresponds to a natural gas density of 160.2 kg/m^3. This assumption is based on the expected temperature and pressure of natural gas in a full vehicle storage tank.

$$\dot{m}_{comp} = scfm * \rho_{NG}(T = 25°C, P = 100kPa) \tag{1}$$

.

$$comp_{gal/day} = \rho_{NG}\left(T = 25°C, P = 24,820kPa\right) / \dot{m}_{comp} \tag{2}$$

Combining Equations 1 and 2, converting units and substituting values yields the relationship between the flow rate of the compressor and the number of CNG gallons which can be produced in one day. The result is shown in Equation 3.

$$comp_{gal/day} = 43.4\left[\frac{gal * \min}{day * ft^3}\right] * scfm \tag{3}$$

6.1.1.2 Compressor Costs

Budgetary estimates for compressors of various sizes are given in Table 22. These values were obtained via direct supplier contact and published literature. In order to achieve the greatest return on investment, the compressor with the lowest cost per $scfm$ is selected for analysis. The CNG -75, produced by ANGI, has the lowest cost per$sfcm$, at \$760, and is selected for analysis.

Table 22 Budgetary Estimates for NG Compressor

Manufacturer	Compressor	Flow Rate (scfm)	Max Pressure (psia)	Gallons per day	Cost ($)	$Cost_{scfm}$
P.C. Mckenzie	05H25NGSX	28	5000	1215	52,000.00	1,857
	05H25NGDX	56	5000	2430	87,000.00	1,554
Fuel Maker	FM4 -fuelmaker	10	3000	434	10,000.00	1,000
ANGI International	CNG-10	19	4500	825	31,460.00	1,656
	CNG-20	39	4500	1693	52,201.00	1,338
	CNG-50	59	4500	2561	59,111.00	1,002
	CNG-75	79	4500	3429	59,948.00	759
Greenfield	B65	99	4500	4297	98,400.00	994
	B65	125	4500	5425	100,400.00	803

The total cost of the compressors,$Cost_{comp}$, and the total flow rate, $scfm_T$, are dependant on the number of CNG-75 compressors in the system and the CNG-75 specifications. The total compressor cost and flow rate of system are given by of the Equations 4 and 5 respectively.

$$Cost_{comp} = N_{comp} * 60,000[\$] \tag{4}$$

$$scfm_T = N_{comp} * 75[scfm] \tag{5}$$

6.1.1.3 Work Required Operate Compressor

The work required to operate a compressor for a specified mass flow rate is given by Equation 6. The specific heat of natural gas, Cp_{NG} , at ambient temperature is 2.25 kJ/kg-K and the specific heat ratio, k, is 1.30. Additionally, the efficiency of the compressor, η_{comp} , is estimated to be 80%.

$$W_{comp} = Cp_{NG} * T_{atm} * \dot{m}_{comp} * \left(\left(\frac{P_{final}}{P_{atm}} \right)^{\left(\frac{k-1}{k}\right)} - 1 \right) / \eta_{comp} \tag{6}$$

Combining Equations 6 and 1, converting units and substituting values yields the relationship between the $scfm$ and the work required to operate a compressor and is shown in Equation 7.

$$W_{comp} = 0.656 \left[\frac{kW * \min}{ft^3} \right] * scfm \tag{7}$$

<u>6.1.1.4 Electricity Cost per Gallon</u>

Electricity is required to operate the compressor(s) and imposes a cost increase per gallon of CNG produced. The additional cost per gallon for the electricity consumed by the compressor(s) is calculated using Equation 8. The electricity rate, E_{rate}, is typically rated in \$/kW-h and is estimated to be 0.06841 based on the average rates paid for businesses companies in Michigan for 2007. The flow rate of the compressor falls out of the computation and results is a cost of 0.02482 \$/gal.

$$Cost_{electricity} = E_{rate} * W_{comp} * / comp_{gal/day} = 0.025[\$ / gal] \tag{8}$$

6.1.2 Storage

A CNG ground storage system typically has a maximum design pressure of 5,500 psi and operates at 4,500 psi. The vessels are mounted in a steel frame with isolation, drain, and relief valves. Compressor discharge pressure must be able to fill the storage to a minimum of 4,500 psi at 70° F. The vessels must conform to the ASME UPV Code Section VIII, Division 1, Appendix 22.

In smaller CNG stations, high-pressure ground storage is used to decrease required compressor capacity. For larger stations, the incremental cost of compressor capacity is less than the incremental cost of additional storage cylinders. The storage cylinders are still used in larger stations to prevent excess compressor cycling and are usually connected as a single bank or buffer (EA Engineering, Science, and Technolgy, Inc., 1997). In the case of the large automotive manufacturer, the CNG station will be small because it is essentally a pilot. This fact implies that the level of ground storage should be of a sufficient size to refuel at least one vehicle. The following sections will present the relavent calculations for storage tank cost and the total amout of natural gas storage fot the refueling station.

6.1.2.1 Storage Tank Cost

The size of a storage tank is rated by the number of dispensable gallons at 3,600 psi. Table 23 shows budgetary estimates for two available tanks. The 80 gallon tank produced by ANGI is used for this analysis because it provides the best return on investment. Using the specifications for the 80 gallon tank, Equation 9 computes the total cost of storage for the refueling station based on the number of storage tanks denoted by $N_{S-tanks}$.

Table 23 Storage Tank Budgetary Estimates

Manufacturer	Size (Dispensible gallons @ 3600 psi)	Max Pressure (psia)	Cost
ANGI	40	4500	60,003.00
C P Industries	80	4500	86,400.00

$$Cost_{Storage} = N_{S\text{-}tanks} * 80,000[\$] \tag{9}$$

6.1.2.2 Storage Tank Size

The amount of natural gas storage, on a per mass basis, is necessary for this analysis. Equation 10 computes the total mass for the entire system for a given number of storage tanks. The density of NG at 31,026 kPa (4,500 psi) is 200.8 kg/m^3.

$$\begin{aligned} m_{storage} &= N_{S-tanks} * 80\left[gal\right] * \rho(T = 25°C, P = \text{ 31,026 kPa}) \\ &= 121.6 \text{ [kg]} * N_{S\text{-}tanks} \end{aligned} \tag{10}$$

6.1.3 Additional Equipment

6.1.3.1 Dispensers

The dispensers connects the onsite CNG system to the storage tanks onboard the vehicle. The onsite CNG system must have at least one dispenser, but the maximum number of dispensers is not limited. Multiple dispensers allow the system to service vehicles simultaneously, but each vehicle is refueled at a decreased rate. Dispenser cost is approximately $3,000 per unit based on contact with suppliers. The total cost of the Dispensers, $Cost_{Dispenser}$, is computed using Equation 11.

$$Cost_{dispenser} = N_{dispener} * 3{,}000[\$] \tag{11}$$

6.1.3.2 Sequencer

The sequencer controls the flow into and out of the storage tanks. If there are no vehicles at the refueling station, the sequencer runs the compressor until the storage tanks are full. If there is a vehicle at the refueling station, the sequence panel directs NG flow out of the storage tanks and into the vehicle. If the storage tanks are empty, the sequence panel directs NG flow directly into the vehicle. The refueling time for a CNG vehicle should be roughly equivalent to the refueling time of a diesel vehicle if there is sufficient natural gas in the storage tanks. If there is insufficient natural gas in ground storage, refueling time is dependent on the size of the compressor. Based on direct supplier contact, the cost of a sequencer is estimated to be $3,500. Gas cooler, machine controls, and local shutdown monitoring are integrated into the sequencer. Assuming that each compressor needs a sequencer, the total cost of all sequencers for the system, $Cost_{sq}$, is computed using Equation 12.

$$Cost_{sq} = N_{comp} * 3,500[\$] \quad (12)$$

6.1.3.3 Filter and Dryer

Natural gas typically contains water vapor which must be removed to protect critical vehicle and refueling station components. Desiccant dryers are used to ensure the correct water dew point for the application and location. The filter is a discharge separator which coalesces 99.9% of contaminates larger than 0.3 microns in the discharge gas. Filters and dryers are rated to at least 5000 psi. The filter and dryer are housed in a single unit and has a cost of $14,500. The specifications and costs of the filter and dryer were obtained via direct supplier contact. A filter and dyer are required for each compressor, so the total cost of the filer and dryers, $Cost_{filter}$, is given in Equation 13.

$$Cost_{filter} = N_{comp} * 14,500[\$] \quad (13)$$

6.1.4 Cost Analysis

The total cost of the refueling system is composed of the equipment costs, site design, installation, training, maintenance and tax. This section will present the calculations and assumptions used to generated the equation for total system cost.

6.1.4.1 Equipment Costs

The total cost of the equipment, given in Equation 14, is the sum total of the sequencer(s), filter(s), ground storage(s), and compressor(s) for the entire system. Since the design variables for the system have not been specified at this point, it is convenient to substitute equations from the previous sections to obtain Equation 15. It is important to note that the only design variables are the number of CNG-75 compressors, number of 80-gallon storage tanks, and the number of dispensers.

$$Cost_{equipment} = Cost_{sq} + Cost_{filter} + Cost_{storage} + Cost_{dispenser} \qquad (1)$$

$$Cost_{equipment} = N_{comp} * 78,000[\$] + N_{storage} * 80,000[\$] + N_{dispenser} * 3,000[\$] \qquad (15)$$

6.1.4.2Design, Installation, and training

There is great deal of uncertainty regarding the cost associated with designing and installing an on-site refueling station especially because the physical size and location of the station is not defined. There may be significant effort required to supply the station with necessary utility connections and the ground storage may take up a considerable amount of lot space. It may also be necessary to modify the site to allow for vehicle to access the refueling stations. Although the selection of an appropriate location for the on-site refueling station can mitigate these issues, there are still costs associated with freight, site materials, and installation which must be considered. Based on contact with suppliers, the freight and site materials are estimated to cost $7,000 per compressor. Due to the uncertain nature of the labor required to design and install the system, the labor cost is assumed to be 10% of the equipment cost.

Based on direct supplier contact, the cost of startup and training is assumed to be $4,500 independent of the system size. The total cost for design, installation, and start up of a system, $Cost_{Install}$, is given by Equation 16 .

$$Cost_{Install} = 4,500[\$] + (N_{comp} * 7,000[\$]) + (10\% * Cost_{equipment}) \tag{15}$$

<u>*6.1.4.3 Insurance, Maintenance and Tax*</u>

The refueling station is subject to property tax as "personal property" under the current Michigan Business Tax (MBT). Personal property is defined as machines, equipment, fixtures and signs used by businesses. Property taxes are levied as a millage rate, denote by $millage_{rate}$. A millage rate is levied by both the state and local government. Since the millage rate is dependent on the county of residence, a nominal millage rate of 60 is assumed. The taxable value, denoted by $Value_{Taxable}$, of the property is determined as 50% of market value and is estimated by the City Assessor's office each year. Property taxes for CNG equipment after it has been installed is calculated using Equation 17.

$$PropertyTax_{facility} = Value_{taxable} \div 1,000[\$] * rate_{mil\lg e} = 6\% * Value_{taxable} \tag{16}$$

This tax is incurred every year but decreases over time due to depreciation. A straight-line depreciation model is used for this analysis, which is shown in Equation 17. The scrap value is assumed to be 60% of the initial equipment cost and the useful life span is assumed to be 10 years. These assumptions are based on discussions with equipment suppliers. The resulting depreciation is 4% of the total equipment cost per year.

$$Depricaiton_{yr} = \frac{(Cost_{equipment} - Value_{scrap})}{Lifespan[years]} = 4\% * Cost_{equipment} [\$ / year] \quad (16)$$

The taxable value for the refueling station after a given number of years is then calculated using Equation 16.

$$Value_{Taxable} = 50\% * Cost_{equipment}(1 - .04 * N_{years}) \quad (16)$$

The maintenance and insurance costs for the facility are assumed to be a flat rate of 10% percent of the initial equipment costs per year. Combining the maintenance cost with yearly property tax yields the operational cost, $Cost_{operation}$, of the refueling facility per year and is shown in Equation 17.

$$\begin{aligned} Cost_{operation} &= Cost_{maintenance} + PropertyTax_{facility} \\ &= Cost_{equipment} * (0.1 + 0.03 * (1 - 0.04 * N_{years}))[\$ / year] \end{aligned} \quad (17)$$

Section 1342 of the Energy Policy Act of 2005 provides for an Alternative Fuel Infrastructure Tax Credit. This provision provides a tax credit for business equal to 30% of the cost of alternative refueling property, up to $30,000. Qualifying alternative fuels are natural gas, propane, hydrogen, E85, or biodiesel blends of B20 or more. The credit is effective on purchases put into service after December 31, 2005 and it expires December 31, 2009. The minimum investment in a CNG facility will be at least $100,000, so the maximum tax credit is assumed and is represented with Equation 17.

$$TaxCredit_{facililty} = 30,000[\$] \tag{17}$$

6.2 CNG Vehicles

The natural gas engine market has focused primarily on transit buses and medium-duty applications. Expanding into the heavy truck and articulated bus markets requires increased engine power and torque. To meet these requirements, Cummins Westport Incorporated (CWI) has developed a new and larger engine platform based on its PLUS technology. PLUS technology provides state-of-the-art engine control and operation along with advanced diagnostic capabilities. CWI's C Gas Plus 8.3 L and B Gas Plus 5.9 L natural gas engines have demonstrated market acceptance among natural gas fleet operators. The Cummins ISL (8.9 L) diesel engine is also a market-accepted product (Kamel, July 2005).

6.2.1Vehicle efficiency

The trade-off from going to spark ignition operation is that vehicle fuel economy is reduced by 10% to 25%. The reductions are highest at idle because diesel engines can operate without a throttle because of in-cylinder fuel injection and stratified charge combustion. This fact greatly lowers pumping losses relative to spark ignited engines which must use a throttle and don't have stratified charge combustion (EA Engineering, Science, and Technolgy, Inc., 1997). The compression ratio of a natural gas engines must be reduced which increases fuel consumption under all engine load conditions. At high engine loads and speeds, the efficiency difference between the two types of engines is small (New York State Energy Research and Development Authority, 1997).

Viking Freight reported the fuel economy of the diesel trucks was approximately 6.1 mpg over the standard UDDS and 7.9 mpg over a custom drive cycle. The fuel economy of the natural gas trucks was approximately 4.8 mpeg over the UDDS and 6.3 mpeg over the Viking cycle, which represents an average energy based fuel economy penalty of 21% and 20%, respectively (Lyford-Pike, 2003). In a test performed by the NREL, average fuel economy was 5.17 mpeg for the natural gas trucks and 6.73 mpg for the diesel trucks. This represents a 23.2% fuel economy penalty for the natural gas trucks (Lyford-Pike, 2003). Newer engines, such as the Cummins Westport ISL G, are expected to have greater fuel economy because they use a stoichiometric burn with exhaust gas recycling technology.

Recent advances in engine technology and current tax incentives for new alternative fuel vehicles make new engine purchase more economical than retrofitting older diesel vehicles. For this reason, an efficiency penalty for natural gas, $mpg_{penalty}$, of 15% is assumed for this analysis.

6.2.2 Vehicle Range

Even if natural gas is compressed to 3600 psi, the fuel system needs at least 3.35 times the fuel storage volume to produce vehicle range equivalent to diesel. CNG cylinders are also constrained to spherical or cylindrical shapes to withstand the large internal pressure which makes tanks difficult to mount in traditional locations (EA Engineering, Science, and Technolgy, Inc., 1997). Since the fuel tanks are typically located on the sides of the vehicle, drivers may have a difficult time maneuvering the vehicle if the outer dimensions are increased. Since the volumetric fuel storage is constrained, the result is a drastically reduced vehicle range for CNG vehicle. Reduced vehicle operating range is the greatest physical drawback for CNG, which stems from CNG's low energy storage density even at high pressures. Viking Freight achieved a range of over 200 miles with a fuel storage design consisting of nine CNG cylinders with total capacity of 49.8 DGE (Lyford-Pike, 2003)

All CNG cylinders must meet the U.S. Department of Transportation's National Highway Traffic Safety Administration (DOT/NHTSA) developed Federal Motor Vehicle Safety Standard No. 304, Part 571. The latest commercially available tanks measures 21.2 inches (539 mm) in diameter with lengths up to 120 inches (3048 mm). These tanks represent the lowest cost per standard cubic foot of storage. Having a fewer number of large tanks on a vehicle results in a reduction in plumbing and mounting hardware as well. The 60 in tank is selected for this analysis to provide the most flexibility in vehicle storage volume while still retaining good economies of scale. This tank holds 250.8 liters which is approximately equal to 2,624 Mcf of natural gas or 19 diesel equivalent gallons (DEG).

The range of a CNG vehicle, given in Equation 18, is dependent on the number of fuel storage tanks, $N_{V-tranks}$, the fuel mileage of an equivalent diesel vehicle, and the mpg penalty of natural gas.

$$Range = N_{F-Tanks} * 19.0[DEG] * mpg_{diesel} * (1 - mpg_{penalty}) \tag{17}$$

Based on the survey for HDDV carriers for this application, a diesel mpg of 5.9 is used. The natural gas penalty is 15%, as discussed in the previous section. Two storage tanks are necessary to provide a maximum vehicle range of 190, three provides a range of 285 miles, and four tanks provide a range of 380 miles. More than four storage tanks are not likely to be practical on standard vehicle chassis without severely compromising cargo capacity or driving characteristics.

6.2.3 Incremental Vehicle cost

The incremental vehicle cost, $incost_{vehicle}$, is defined as the additional expense which incurred when purchasing a CNG powered vehicle versus a comparable diesel powered vehicle. The CNG incremental vehicle cost is associated with the engine is the ignition system. The estimated increase in engine price due to the ignition system is $9,500 (Schubert, et al., July 2005). The majority of the incremental vehicle cost is the fuel system due to the storage tanks. The cost of each storage tank is estimated to be $4,000 via direct supplier contact. Incremental vehicle cost is therefore given by Equation 18.

$$\mathrm{incost}_{vehicle} = 9,500[\$] + N_{F-Tanks} * 4,000[\$] \qquad (17)$$

6.2.4 Tax Incentives

Section 1341 of the Energy Policy Act of 2005 provides a tax credit to purchasers of new dedicated AFVs. The tax credit equals 50% of the incremental cost of the vehicle plus an additional 30% of the incremental costs if the vehicle has received a certificate of conformity under the Clean Air Act and meets or exceeds the most stringent standard available for that make and model year vehicle. The tax credit can be applied to vehicle purchases made after December 31, 2005 and it expires December 31, 2010. Since the engine selected for analysis meets the 2010 emissions standards for heavy duty diesel vehicles, a tax credit equal to 80% of the incremental vehicle cost is assumed. The maximum incremental vehicle cost for vehicles weighing more than 26,000 lbs is $40,000. Equation 18 shows the tax credit per vehicle assuming that the incremental cost is less than $40,000.

$$\mathrm{TaxCredit}_{vehicle} = 80\% * \mathrm{incost}_{vehicle} \tag{18}$$

Vehicles are also subject to the same property tax as the refueling station. Using the same deprivations schedule and formula for taxable value, the total property tax owed for a given number of vehicles is shown in Equation 19. It is important to note that this tax only represents the increase in tax which must be paid due to the more expensive CNG vehicle.

$$PropertyTax_{Vehicles} = 6\% * (1 - .04 * N_{years}) * N_{vehicles} * incost_{vehicle} \tag{19}$$

6.2.5 Incremental Maintenance Costs

Basic maintenance task created by introduction of CNG consists of periodic inspections of the high-pressure natural gas storage cylinders, pressure relief valves, natural gas lines and pressure regulators, and the engine ignition system (EA Engineering, Science, and Technolgy, Inc., 1997). The remaining maintenance costs, including oil changes, filter changes, coolant filters, value adjustments, and vehicle chassis, are considered to be equivalent to diesel powered vehicles. Cummins Westport estimates that the incremental maintenance costs of the ignition system will be $1,650/year. The yearly maintenance on the CNG storage system is estimated to be $1,500. Equation 20 shows the incremental yearly maintenance cost for a CNG powered vehicle versus a comparable diesel powered vehicle

$$\mathrm{incost}_{\mathrm{maintenance}} = 3{,}150[\$ / \, year] \tag{20}$$

6.2.6 Change in Tailpipe Emissions

The change in emissions rate, in grams per mile, can be calculated for this application using the EPA software MOBILE6 and the procedure which is outlined in Chapter 5. For on-site CNG, the MOBILE6 emissions rate for short haul HDDV8b class vehicles is used as a baseline emissions rate. The average cost of emissions abatement is also taken from Chapter 5. The expected change in emissions rates for natural gas engines versus standard diesel is taken from the environmental impact index created in Chapter 4. Equation 21 is used to compute the change in cost per mile associated with the expected change in emissions. Table 24 shows the baseline diesel emissions rate for this application, expected change in emissions due to natural gas use, the cost of emissions abatement used in this analysis, and the change in cost per mile. The total cost per mile associated with changes in emissions is approximately $0.13 per mile.

$$\Delta Emission_{cost} = ERate_{Diesel} * \%Change_{CNG} * Cost_{Emission} \tag{21}$$

Table 24 Change in Cost per Mile Associated with Emissions

Emission	Baseline Emisison Rate (g/mi)	% Change vs. Diesel	$ per ton	Change in $ per mile
NO_X	13.003	-30%	14,746.16	**-0.063**
SO_X	0.326	-100%	60,609.51	**-0.022**
CO	3.821	-90%	590.38	**-0.002**
CO_2	1638.2	-23%	15.29	**-0.006**
PM_{10}	0.350	-90%	120,754.87	**-0.042**
HC	0.603	1000%	954.00	**0.006**
			Total:	-0.129

6.3 Change in Fuel Costs

The change in fuel cost for using CNG versus diesel is estimated using the average fuel economy of each type of vehicle and the relative price of natural gas when it is compressed onsite. The diesel fuel economy is estimated from the survey of HDDV. The fuel economy of the CNG vehicle is assumed to be 15% less than the fuel economy of an equivalent diesel vehicle. The following sections will outline the calculation of the DEG, conversion of natural gas rates, variability of natural gas prices, and the estimated change in cost per mile for on-site CNG.

6.3.1 Diesel Equivalent Gallon

The Diesel Equivalent Gallon (DEG) represents for the number of gallons of a particular fuel which is required to equal the energy content of one gallon of diesel and is represented by Equation 22.

$$gal_{diesel} = gal_{CNG} / DEG_{CNG} \tag{22}$$

The DEG is based on the energy density of the fuel and can be calculated for CNG using Equation 23. The lower heating value, LHV, of natural gas is 50.2 MJ/kg and the LHV of diesel fuel is 43.0 MJ/kg. The density of diesel fuel is 830 kg/m^3. The density of natural gas a temperature of 25°C and pressure of 24,850 kPa (3,600 psi) is 160.6 kg/m^3. The resulting DEG for CNG at 3,600 psi is 4.43.

$$DEG_{CNG} = \frac{LHV_{Diesel} * \rho_{Diesel}}{LHV_{NG} * \rho_{NG}(T = 25°C, P = 24,850kPa)} = 4.43 \qquad (23)$$

6.3.1.1 Natural Gas Cost – Utility Conversion

The natural gas wellhead price is computed in dollars per thousand cubic feet, or $/Mcf, assuming the gas is at standard temperature and pressure. Utility companies also charges for natural gas based on $/Mcf assuming standard conditions. In order to compare the cost of natural gas versus diesel, this price must be converted into price per US gallon. Equation 24 relates the cost of natural gas per Mcf to gal_{US}.

$$\begin{aligned} &NG_{\cos t}\left[\$ / gal_{US}\right] = \\ &NG_{\cos t}\left[\$ / Mcf\right] * \left[\frac{Mcf}{28.317m^3}\right] * \frac{\rho_{NG}(T = 25°C, P = 24,850kPa)}{\rho_{NG}(T = 25°C, P = 100kPa)} * \left[\frac{0.003785\mathrm{m}^3}{\mathrm{gal_{us}}}\right] \end{aligned} \qquad (24)$$

The natural gas rate for large companies in Michigan, as of June of 2007, is approximately 12.00 \$/Mcf which corresponds to a natural gas cost of 0.40 $\$/gal_{US}$. This rate is based on the published rates from Michigan utility companies. This cost per gallon is used for the analysis of the TBL business case but it is recognized that the price of natural gas is expected to fluctuate significantly over the useful lifespan of the facility. This issue is dealt with in the next section.

6.3.2 Variability of Natural Gas prices

The creation of a positive TBL business case for the use of CNG depends on the lower DEG price of natural gas versus diesel. The price of either fuel is extremely difficult to predict which makes long term analysis difficult. Figure 6.1 shows the historic retail price for No. 2 Diesel and the DEG price for natural gas based on the wellhead price. This data was obtained from the US Department of Energy website.

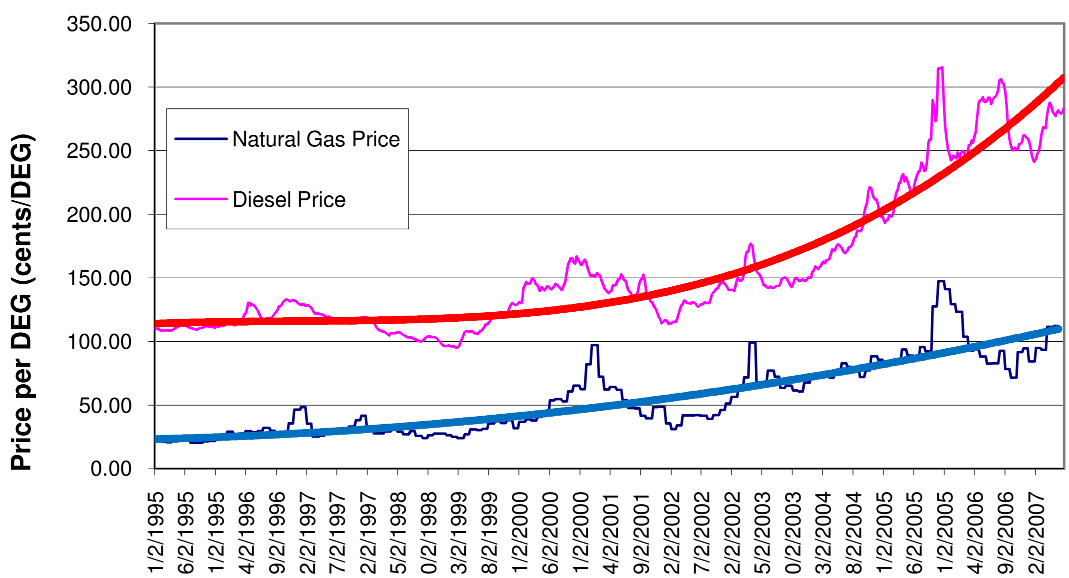


Figure 6.1 Historic Fuel Costs per Gallon

The price ratio between natural gas and diesel has the greatest impact on payback schedule for investment in a CNG facility and vehicles. Many factors can affect the price difference between the fuels such as changes in the volume of imported natural gas, the fuel storage, compression, delivery methods, and fleets buying in bulk (Schubert, et al., July 2005). The price of natural gas as a percentage of the diesel price is shown in Figure 6.2 for the same time period as the historic fuel costs.

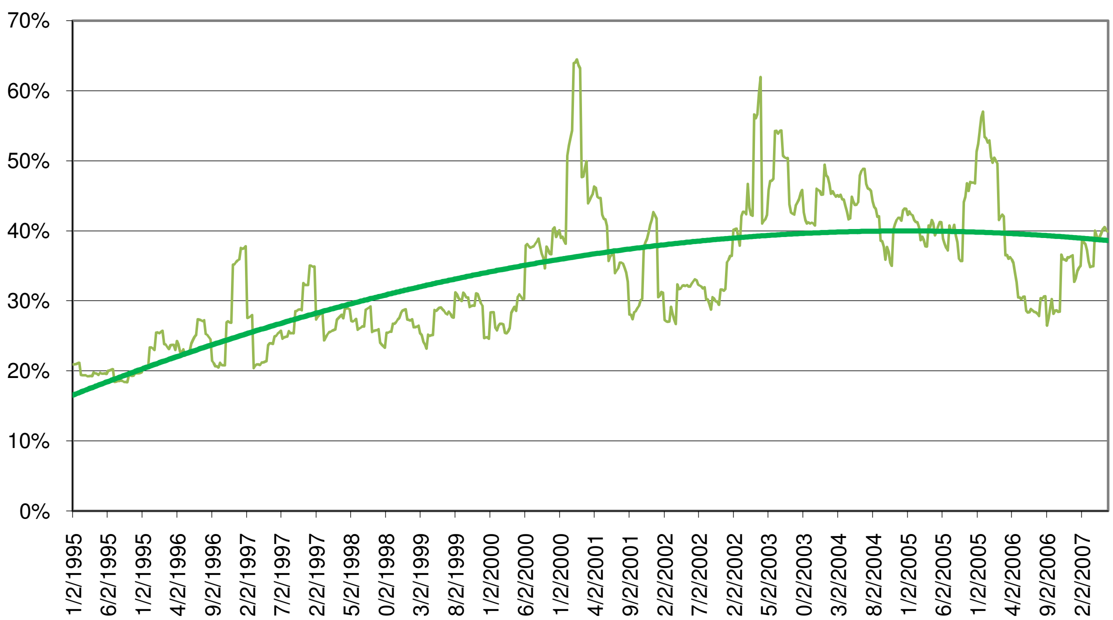


Figure 6.2 Price of Natural Gas as a Percentage of Diesel Cost

It can be seen that the DEG price for natural gas has always been less than 70% of the diesel price, even during extreme price spikes. The DEG price of natural gas from 1995 through 2006 averages 34% of the diesel price with a standard deviation of 9.4%. The price of natural gas, as computed in the previous section, is 0.40 $/gal for June 2007 and the price of diesel averages 3.30 $/gal in Michigan for the same time period. This corresponds to DEG natural gas price which is 54% of the diesel price. Since this percentage is well above the average, using these fuel prices in the TBL analysis for the large automotive manufacturer's application will result in a conservative business case.

6.3.3 Estimated Change in Cost per Mile

The change in fuel cost for CNG versus diesel is computed on a dollar per mile basis using Equation 25. It is important to note that capital investment and operational cost are not included in this metric and will be considered separately.

$$\begin{aligned} \Delta Savings_{mile} &= (Cost_{Diesel} - (Cost_{NG} + Cost_{electricity}) * DEG_{NG} / (1 - mpg_{penalty})) / mpg_{Diesel} \\ &= 0.184[\$ / mile] \end{aligned} \tag{25}$$

The cost of the natural gas is 0.40 $/gal$_{US}$ and the cost of diesel is 3.30 $/gal$_{US}$, as discussed is previous sections. The fuel efficiency of diesel for the application is 5.9 miles per gallon which is taken from the survey data. The natural gas fuel economy penalty is assumed to be 15% as discussed in previous sections.

Section 1113 of the Highway act provides for a tax credit of $0.50 per DEG paid to the seller, blender or user of the alternative fuel. This tax credit is currently set to expire on 9/30/2009. There is also is an excise tax of $0.183 imposed on each DEG of CNG. The tax credit can be computed on a per mile basis using Equation 26.

$$TaxCredit_{fuel} = (0.50[\$] - 0.183[\$]) / (mpg_{Diesel} * (1 - mpg_{penalty})) \\ = 0.0632[\$ / mile] \tag{26}$$

6.4 Simple Payback Period

6.4.1.1 Total Capital Investment

The total capital investment for the refueling station, shown in Equation 27, is the sum of the equipment costs, installation costs, and incremental vehicle costs.

$$Capital_{\cos t} = Cost_{equipment} + Cost_{Install} + N_{vehicles} * \text{incost}_{vehicle} \tag{27}$$

Substituting in appropriate values for each variable yields Equation 28. It is important to note that the capital costs are a function of the number of compressors, dispensers, ground storage tanks, vehicles, and the number of fuel tanks per vehicle.

$$Capital_{\cos t} = N_{comp} * 92,800[\$] + N_{dispenser} * 3,300[\$] + N_{storage} * 88,000[\$] \\ + N_{vehicles} * (N_{F-Tanks} * 4,000[\$] + 9,500[\$]) + 4,500[\$] \tag{28}$$

This capital investment is offset by the tax credit recouped in same year as the initial investment. This tax credit, shown in Equation 29, is a function of the number of vehicles and the number of storage tanks for each vehicle.

$$TaxCredit_{Property} = 30,000[\$] + N_{vehicles} * 80\% * (N_{F-Tanks} * 4,000[\$] + 9,500[\$]) \quad (29)$$

6.4.1.2Miles Driven per year

In order to compute the change in operational cost per year, the total capacity of the refueling station must be computed. The capacity of the refueling station is determined as the number of miles per year which it can support and is computed using Equation 30. The number of operational days in a year is estimated to be 288 based on a 6 day work week and 48 weeks per year. The compressor utilization term, U_{comp}, is percentage of day the when the compressor is actually running. When the appropriate values are substituted, the number of miles per year is given by Equation 31.

$$N_{miles/yr} = \frac{comp_{gal/day} * 288[days / year] * U_{comp} * mpg_{diesel} * (1 - NG_{penalty})}{DEG} \quad (30)$$

$$N_{miles/yr} = U_{comp} * N_{comp} * 1,061,232[miles / yr] \quad (31)$$

6.4.1.3 Approximate Equipment Utilization

The compressor usage can be approximated based on an average speed of 25 mph and 12 hours of drive time. The maximum number of miles a vehicle can drive under these constraints is 300. The maximum number of miles which can be supported by one 75 $scfm$ is 3,685 miles per day, which is based on the maximum compressor production the expected mpg of the vehicle. Equation 26 relates the ratio between the number of compressors and the number of vehicles to the compressor utilization.

$$U_{comp} \approx \frac{N_{vehicles} * 300[miles]}{N_{comp} * 3685[miles]} \tag{37}$$

Because the on-site CNG refueling station is quick fill, the actual value of the compressor utilization term will be dependent on the ground storage capacity, the number of compressors, the number of vehicles, vehicle storage capacity, number of dispensers, distance driven by each vehicle and the schedule of vehicle refueling. Because the interaction between these variables is complex and difficult to quantify mathematically, a discrete event simulation is used to calculate the compressor utilization. Details and results of this simulation are presented in the next section.

6.4.1.4 Annual Economic Savings

The annual economic savings for the on-site refueling station is computed using Equation 38. This equation assumes that the cost per mile is positive, which indicates a reduction in the operating cost of the vehicle. If the change in cost per mile is negative, this equation will result in an annual cost for operating on-site CNG. The tax credit for CNG is also assumed to be positive based on current market conditions. If the tax credit is repealed, this variable will be negative which represents the standard fuel tax per mile.

$$Savings_{annual} = (\Delta Savings_{mile} + TaxCredit_{fuel}) * N_{miles/yr} \\ -(PropertyTax + Cost_{maintenance} + incost_{maintenance}) \quad (38)$$

When the appropriate values are substituted into the previous equation, the result is Equation 39. It can be seen that the annual savings are dependent on number of compressors, dispensers, ground storage tanks, vehicles, and the compressor utilization.

$$Savings_{annual} = N_{comp} * (264,247 * U_{comp} - 10,140[\$/yr]) - N_{dispenser} * 390[\$/yr] \\ -N_{storage} * 10,400[\$/yr] + N_{vehicles} * 3,150[\$/yr] \quad (39)$$

6.4.1.5 Annual TBL Savings

The annual TBL savings are computed in the same manner as the economic savings but include the dollar value assigned the reduction in tailpipe emissions. Equation 40 represents the calculation for the TBL annual savings and Equation 41 represents the calculation with appropriate values substituted.

$$TBLsavings_{annual} = (\Delta Savings_{mile} + TaxCredit_{fuel} + \Delta Emission_{\$/mile}) * N_{miles/yr} \\ -(PropertyTax + Cost_{maintenance} + incost_{maintenance}) \quad (40)$$

$$TBLsavings_{annual} = N_{comp} * (401,146 * U_{comp} - 10,140[\$/yr]) - N_{dispenser} * 390[\$/yr] \\ -N_{storage} * 10,400[\$/yr] - N_{vehicles} * 3,150[\$/yr] \quad (41)$$

6.4.1.6 Simple Payback Period

The economic simple payback period, shown in Equation 35, for the on-site refueling station is calculated by dividing the capital investment, less tax property tax credits, by the economic annual savings.

$$SimplePayback = (Capital_{\cos t} - TaxCredit_{Property}) / Savings_{annual} \tag{35}$$

The TBL simple payback period is computed in a similar fashion using Equation 36. The economic and TBL payback periods are computed separately to allow for the system to be optimized for economic performance in real dollars or overall TBL benefit. In either case, the simple payback period is used to evaluate the overall performance of a given configuration of an on-site refueling station and to optimize the design.

$$TBLsimplePayback = Capital_{\cos t} / TBLsavings_{annual} \tag{36}$$

It is important to note that these payback periods do not take into account inflation, changes in fuel costs, or changes in tax structure. The actual revenue streams of the refueling station will be computed, along with the net present value and internal rate of return, after the size and scope of the system have been optimized.

6.5 On-site CNG Model

The key design variables for an onsite refueling system are; compressor capacity, ground storage volume, number of CNG vehicles, vehicle storage volume, shipping lane scheduling, and the number of dispensers. The economic savings associated with CNG is derived from the price differential between diesel and natural gas. Since the total flow rate and utilization of the compressor determines the number of CNG gallons per day which can be produced per day, these variables dominate the design. There is a complex interaction between these variables which is difficult to quantify explicitly. Optimization of the system design is required in minimize the payback period and required investment. A discrete event simulation is used to model these interactions for the period of one week. The onsite CNG model is written in visual basic and embedded in an excel tool. Following sections will explain the model and tools as well as present the system optimization and results.

6.5.1 Model Code and Explanation

The model is written as a Visual Basic macro in an excel workbook. This allows the user to copy and paste shipping lane data form the large automotive manufacturer's current data management system into the model. This is necessary because optimization of the onsite CNG business case requires iterative selection of shipping lanes. Additionally, the excel model functions as a tool for identifying replacement lanes when bundles must be removed in the normal course of business operation.

The model is a discrete event simulation which simulates a six day business week with a given time step, initially set at 5 min. Each operation of the CNG system is divided into sub-routines, specifically; filling the storage tank, reading delivery schedule, simulating vehicle operation, organizing the queue, indexing the queue, refueling vehicles, and processing the data. The entire code is located in Appendix C along with a detailed explanation of each subroutine. Various refueling schemes can be implemented in the model, but for simplicity each vehicle is assumed to refuel every time the on-board storage is less than 60% of maximum capacity. This ensures that each vehicle has enough fuel to complete the longest round trip distance.

Six different types of shipping lanes are selected for the initial simulation. Each shipping lane shares the same destination, which is assumed to be the location of the refueling station, and have one-way trip mileages varying from 39 to 110. Each one of these lanes has sufficient traffic to assume that availability and scheduling of shipments is not an issue. To simulate a certain number of trucks, these shipping lanes are combined in sufficient quantities to ensure each truck drives approximately 300 miles per day. The possible delivery times are pulled from the large automotive manufacturer's database and are selected to spread out the anticipated refueling times as much as possible.

6.5.2 Excel Tool

The excel tool was designed so the large automotive manufacturer's shipping and logistics department could copy and paste in shipping lane data from their current data management system. The user can then run the model and a variety of graphical outputs are displayed. These plots aide the user in maximizing the return in investment by providing information on scheduling, vehicle wait times, vehicle refueling time, compressor utilization, storage tank usage, dispenser usage, and vehicle queue statistics.

6.5.2.1 Delivery and Departure Schedule

Due to limited range, CNG vehicles must be refueled often. This can present a significant logistical problem. The refueling equipment may be located at the origin or destination, which allows for refueling either before or after delivery respectively. The size of CNG storage tanks on the vehicle and the round trip mileage of the shipping lanes determine how often the vehicle must be refueled. Figure 6.3 shows an example output of the model for a given set of shipping lanes and a refueling station.

Shipping lanes in the large automotive manufacturer's network are typically scheduled for a specific delivery time six days a week. While other types of shipments do exist, they are not good candidates for CNG because it is difficult to maximize the mileage of vehicles utilizing these shipping lanes. The delivery and departure schedule shown in Figure 6.3 indicates the number of shipping lanes which are slated for each time of day. The time of day each shipping lane completes fueling is also indicated. Since this plot represents only one day, the refuel time is averaged over the entire week.

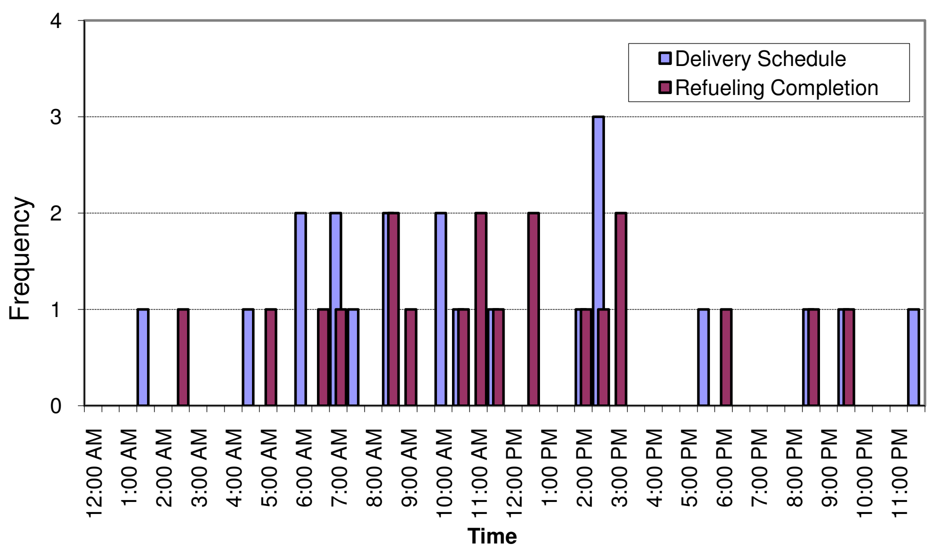


Figure 6.3 Delivery and Departure Schedule

The Delivery/Departure Schedule helps the user to select shipping lanes which are spaced out during the day. Having multiple vehicles arrive at the refueling station simultaneously has an obvious negative impact on the refueling and wait times for each vehicle. Extended periods of inactivity are also undesirable because it is likely that natural gas storage will reach capacity and the compressor will stop producing CNG. This plot can also be used to investigate the effects of increasing compressor flow rate or storage capacity. Increasing the compressor size will decrease the refueling times for vehicles, but may increase the compressor idle time if the storage is insufficient. Likewise, increasing the ground storage capacity of the system may reduce wait times, but only if the compressor has sufficient time to fill the tanks. Increasing the ground storage capacity may also decrease compressor idle time. Because these effects are difficult to predict, additional plots are necessary to better investigate the trade-offs.

6.5.2.2 Queue Statistics

The queue statistics for one week are shown in Figure 6.6. The number of refuels completed is shown in blue and the number of vehicles in the queue is shown in red. When the number of vehicles in queue is greater than the number of vehicles served, vehicles encounter wait times. The number of vehicles waiting to be refueled is shown in red. Since wait times and queues are undesirable, this plot can help indicate what times of day have too many deliveries scheduled. It is important to note that the formation of queue lines do not occur at the same time each day because each vehicle refuels only when its tank is low, not after every delivery. Since each vehicle runs routes of different lengths and frequencies, queue lines are difficult to predict. The model randomly assigns a fuel level to each vehicle at the start of the week, so multiple runs of the model may be necessary to identify times and days of the week which may incur excessive queue lines.

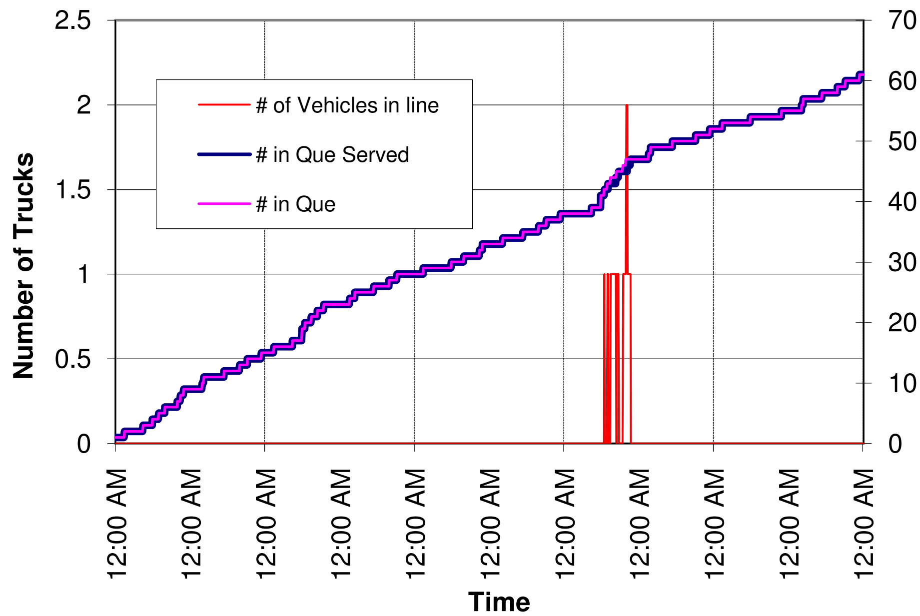


Figure 6.4 Queue Statistics

The queue statistics can also be utilized to investigate the effects of increasing compressor capacity or ground storage volume. Increasing either will increase the system's capacity to refuel vehicles. This capacity increase should decrease the number of vehicles in the queue, but will increase the cost and decrease the utilization of the system. Similarly, the queue statistics can be used to investigate the effects of increasing the vehicle storage. Increasing the vehicle storage capacity will increase the range of the vehicle. This will allow the vehicle run more shipping lanes before refueling is necessary, reducing the number of refuels the system must deliver for a given week. The refueling time for each vehicle, however, increases. This may result in more vehicles in the queue. This affect is highly dependent on the compressor size and ground storage volume, so the net gain or loss is ambiguous.

6.5.2.3 Dispenser Utilization

The number of vehicles in the queue is highly dependent on the number of fuel dispensers. The number of fuel dispensers does not increase the capacity of system, but allows multiple vehicles to be refueled at the same time. This may avoid queue lines, but also increases the refueling time for each vehicle. The extended refueling time may, in turn, increase the queue line for vehicles which arrive later. Figure 6.7 shows the dispenser utilization as a percentage of time in which a given number of vehicles are using the facility. This information can be used to determine if another dispensing unit is needed or if too many have been added already. It also provides a general sense of system utilization if there is a large percentage of time in which zero dispensers are being used. This is not a complete picture of system utilization, however, because the compressors may be working to fill ground storage

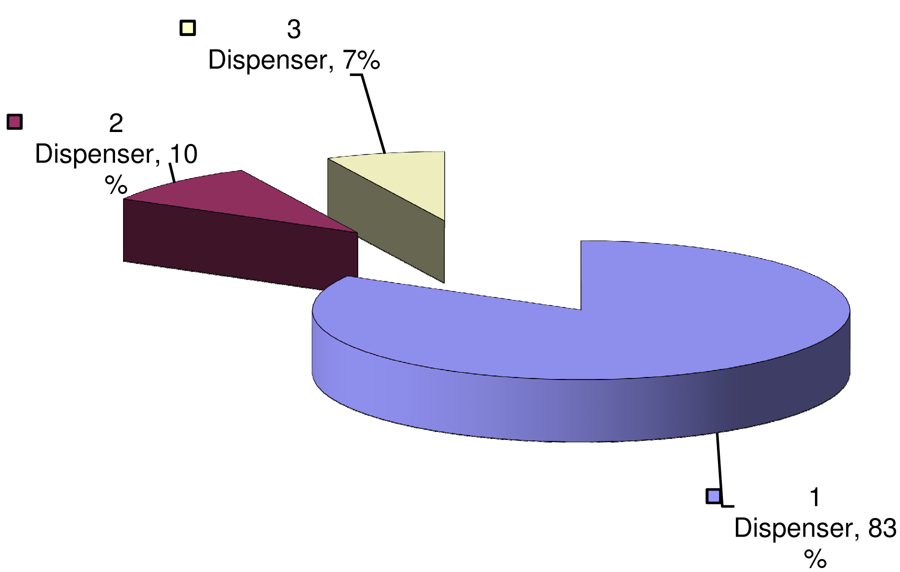


Figure 6.5 Dispenser Utilization

6.5.2.4 Refueling and Wait Times

The average refueling and wait times for a 24 hour period are shown in Figure 6.4. The wait is the average time, in minutes, that a vehicle has to wait before it can hook up to a refueling station. This metric only includes times greater than zero, i.e., only the vehicles that must wait in queue before refueling are included in the average wait time. The refueling time is measured from the moment each vehicle enters the queue to the moment refueling is completed.

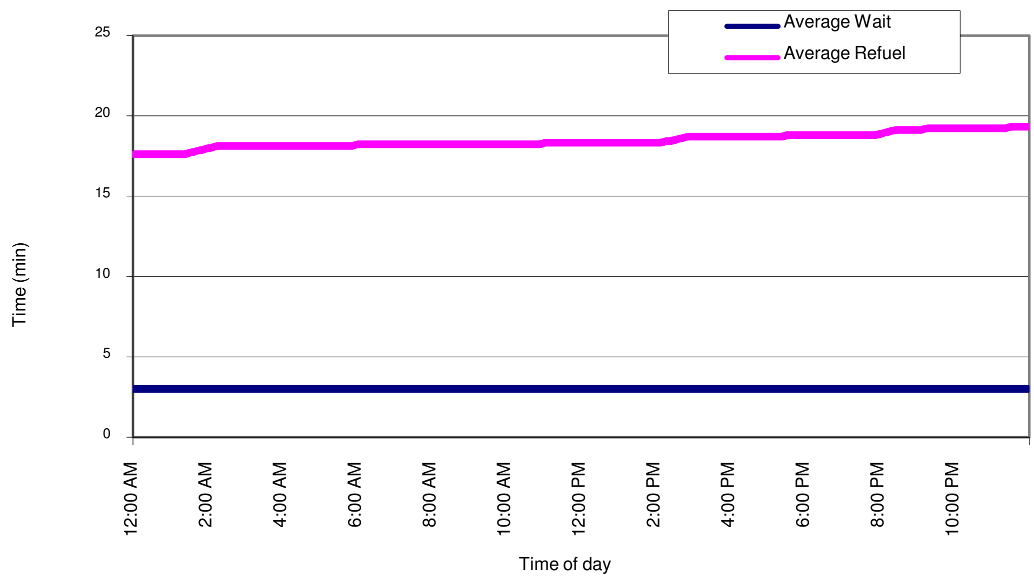


Figure 6.6 Refueling and Wait Times

6.5.2.5 Dispenser Utilization

The key metric for the optimization of an onsite CNG system is the compressor utilization. The compressor operates whenever there is a vehicle at the refueling station or the ground storage is not full. The best way to optimize the system is to select shipping lanes in such a way that vehicle refuels are spaced out evenly throughout the day and ensuring that the mileage of the shipping lanes match the compressor capacity exactly. This would essentially be a time-fill system with no ground storage at all. It is not practical, however, to assume a high level of efficiency can be achieved with this method. Any scheduling conflicts or delays will result in significant refueling times and periods of inactivity, both of which are highly undesirable. Adding additional ground storage eases the scheduling requirements by allowing the compressor to run while no vehicles are refueling and speeding refueling times. Ground storage, however, is extremely expensive and must be kept to a minimum if the system is to have a reasonable payback period.

Figure 6.5 shows the compressor and ground storage usage for the system over the course of one day. Similar plots can be generated for each day of the week. Upper and lower limits for the storage tanks are set in the model. The upper limit represents the point at which the sequencer would recognize that the ground storage is full and shut the compressor off. The lower limit represents the point at which the sequencer will stop filling the storage tanks and divert natural gas directly to vehicles at the refueling station. If the natural gas in ground storage is less than that required by the vehicles being refueled, the ground storage will be emptied into the vehicles. This process occurs rapidly due the pressure differential between the ground and vehicle storage and is seen a steep drop in the ground storage utilization. When the ground storage is below the upper limit and there is no vehicle at the refueling station, the compressor runs and fills the storage. This is seen as an upward slope in the ground storage utilization, the magnitude of which is controlled by the size of the compressor.

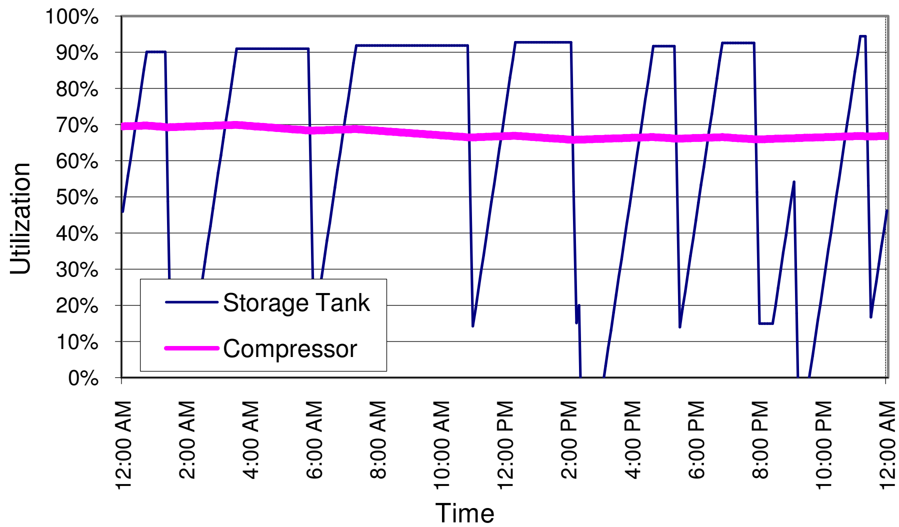


Figure 6.7 Compressor / Storage Tank Utilization

6.5.3 Model Optimization and Results

There are 5 key design variables to consider when optimizing the system; the number of compressors, vehicles, ground storage tanks, dispensers, and the number of fuel tanks per vehicles. All of these variables will have an impact on the compressor utilization, capital costs, and annual savings. The compressor utilization, in particular, is an unknown function of these variables and must be determined from the model. The compressor utilization is also bounded by the constraint that the system be “quick-fill” as opposed to “time fill”. While compressor utilization close to 100% is certainly possible, the refueling time of each vehicle will suffer greatly. Since the company’s shipping business is time sensitive, any refueling time in excess of 30 minutes is considered “time-fill” and therefore unacceptable. The overall goal however, to produce a system with refueling times closer to that of diesel vehicles.

The visual basic model takes approximately 1.5 minutes to run on a standard desktop when a 5 minute time step is selected for the simulation. This makes evaluation of all possible combinations of key design variables impractical. It is found through deduction and experimentation that the numbers of compressors, vehicles and ground storage tanks have the strongest impact on the simple payback. There is also an inverse relationship between the simple payback period and the refueling time. Based on these conclusions, nominal values for the number of vehicle storage tanks and dispensers are chosen, and the remaining design variables are optimized for the quickest payback period. The numbers of compressors, vehicles, and ground storage tanks are then be fixed at their optimal values and the refueling time will be minimized by varying the number of vehicle storage tanks and dispensers. This strategy is not likely to produce the absolute quickest payback period or refueling time, but is a necessary compromise between these competing goals and required simulation time.

6.5.3.1 Number of Compressors, Vehicles, and Storage Tanks

The number of 75 $scfm$ compressors considered in this optimization is 1, 2, 3, and 4. While the results do indicate that better economies of scale may be gained by more compressor capacity, the limitation of available Capital as well as limitation on available short hauls shipping lanes makes four or more compressors impractical. The number of 80 gallon ground storage tanks considered was 1, 2, and 3. The number of vehicles simulated for each compressor varied as each compressor configuration is capable of supporting a different number of vehicles. The number of dispensers is fixed at 2 and the number of fuel tanks per vehicle is set at 4. Simulations are run for each combination of design variable, and the results are evaluated in terms of economic simple payback. The payback periods for the single-compressor configurations are shown in Figure 6.8.

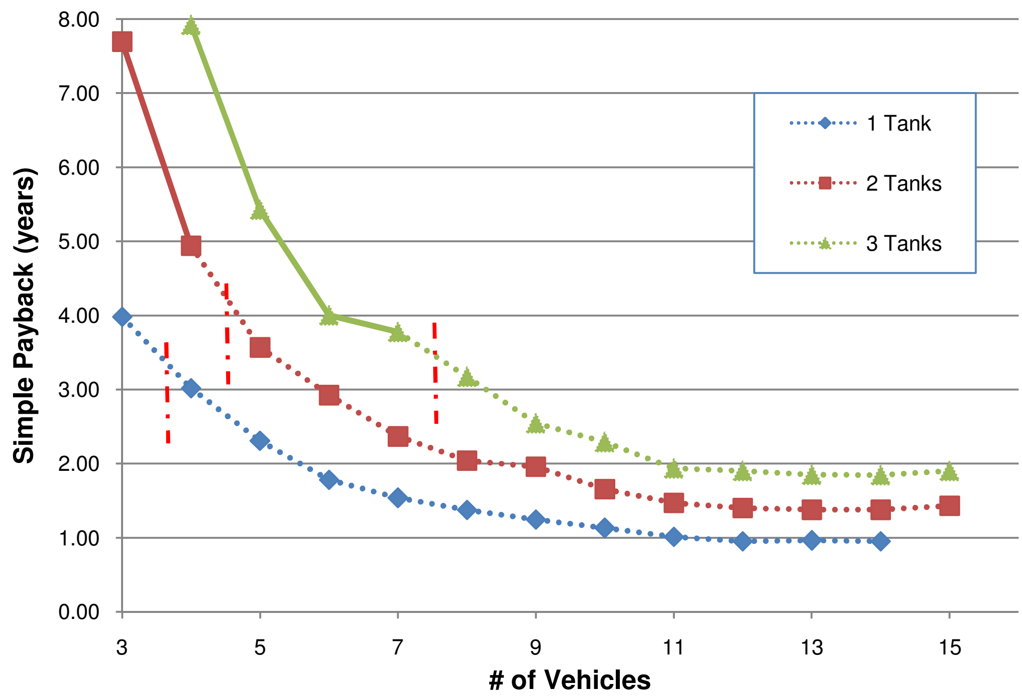


Figure 6.8 Single Compressor - Simple Payback versus # of Vehicles

The red break lines indicate the point at which the system exceeds the "quick fill" constraint and becomes "time fill". It is interesting to note that the addition of storage tanks increases the number of vehicle which can be supported before the "quick fill" constraint is violated. In the case of 3 storage tanks and 7 NG vehicles, the simple payback for a single compressor is actually the fastest despite the higher capital costs. The minimum payback period for a "quick fill" refueling station with a single compressor is approximately 3.8 years. The payback periods for the two-compressor configurations are shown in Figure 6.9.

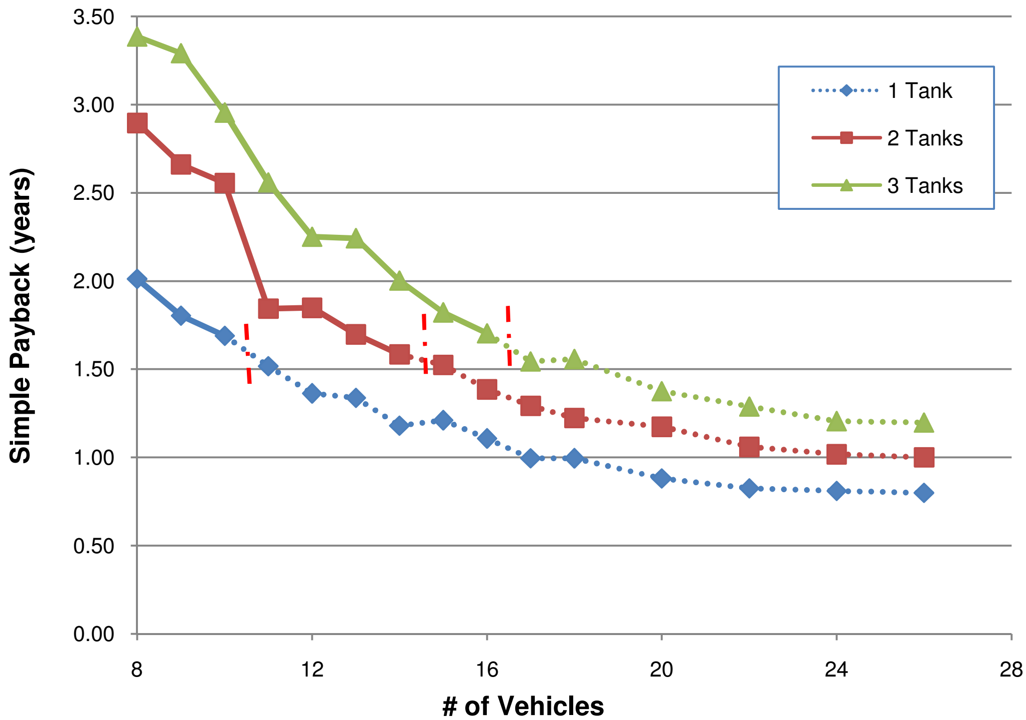


Figure 6.9 Dual Compressors – Simple Payback versus # of Vehicles

. For two compressors, it can be seen that the addition of a second storage tank dramatically increases the number of vehicles which can be supported before the “quick fill” constraint is violated while the addition of the third tank only provides a marginal increase. The shortest payback period before the “quick fill” constraint is violated for each storage tank/vehicle configuration is very small and the quickest payback period which can be expected from a two compressor system is approximately 1.6 years. This represents a significant improvement over the single compressor system. The payback periods for the three-compressor configurations are shown in Figure 6.10.

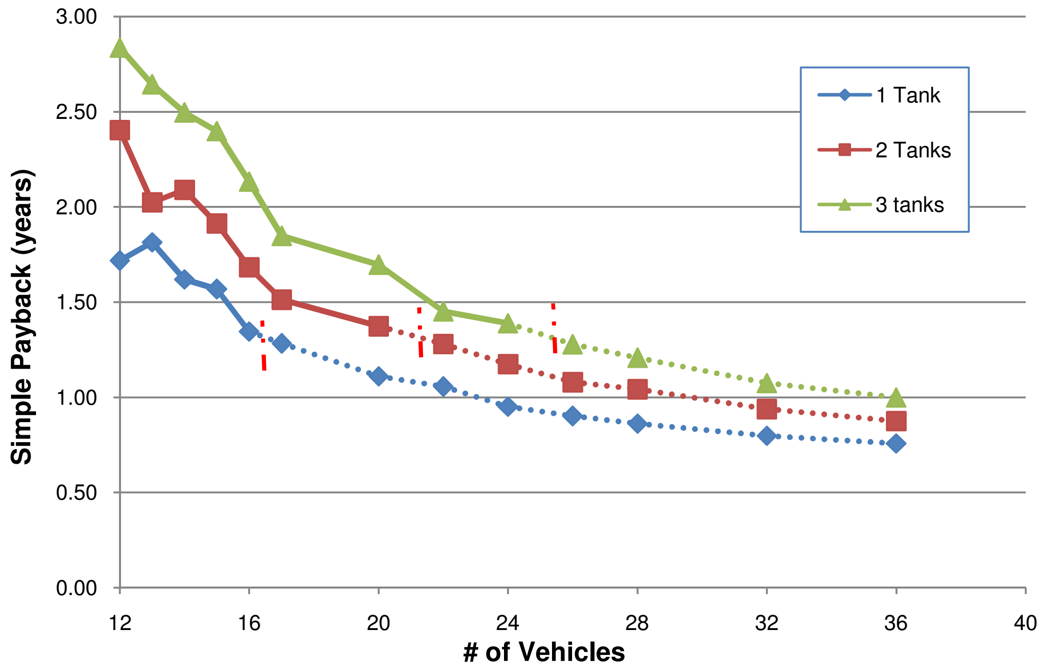


Figure 6.10 Three Compressors – Simple Payback versus # of Vehicles

For three-compressor configurations, adding a second storage tanks increases the number of vehicles which can be supported before the “quick fill” constraint is violated. Adding a third tank produces roughly the same increase in vehicle capacity. The quickest payback period of all three storage tank / vehicle configurations is roughly equivalent. The quickest payback period which can be achieved with a three-compressor configuration is approximately 1.3 years which represents a slight improvement over the two-compressor configuration. The payback periods for the four-compressor configurations is shown in Figure 6.11

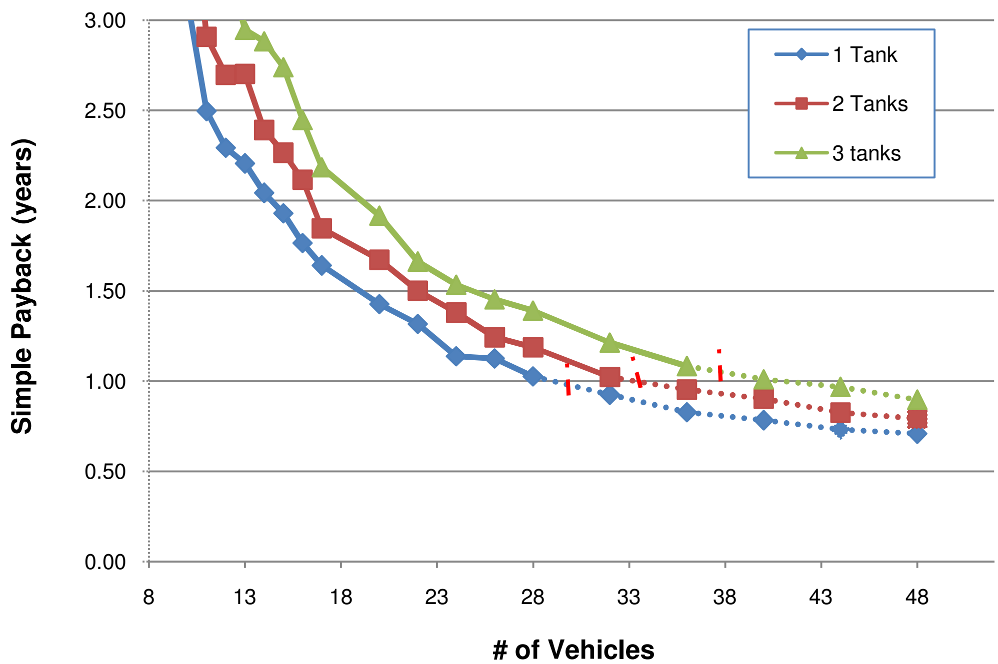


Figure 6.11 Four Compressors – Simple Payback versus # of Vehicles

For four-compressor configurations, adding a second storage tanks increases the number of vehicles which can be supported before the “quick fill” constraint is violated. Adding a third tank produces roughly the same increase in vehicle capacity. This increase is approximately the same magnitude as the increase which is seen the three-compressor configuration. The quickest payback period which can be achieved with a four-compressor configuration is approximately 1.0 years which represents a slight improvement over the three-compressor configuration. The quickest viable payback period, and the number of vehicles, for each compressor configuration is shown in Figure 6.12.

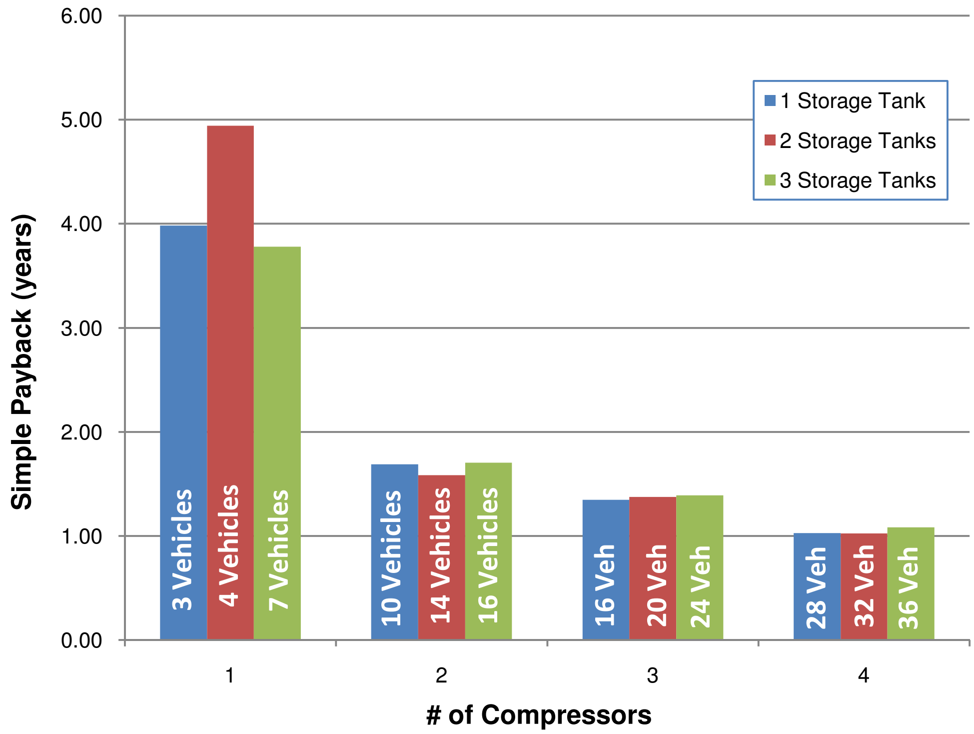


Figure 6.12 Scenarios with Best Simple Payback

It can be seen that increasing the number of compressor and vehicles decreases the payback period. The marginal benefit of each compressor, however, decreases as the number of compressors rises. Increasing the number of compressors also requires an increase in the number of vehicles, which may not be practical.

6.5.3.2 Compressor to Vehicle Ratio versus Utilization

Figure 6.9 shows the utilization for all of the system configurations from the previous section. It can be seen that these values closely correlate to the expected value which was derived from the assumed vehicle mileage per day. An effort is made to assign each vehicle approximately 300 miles per day, but real shipping lanes are used from the company's database. Deviations from the theoretical utilization are expected since each vehicle does not travel exactly 300 miles per day. Inefficiencies in the refueling station due to mismatched components also cause the utilization to drop.

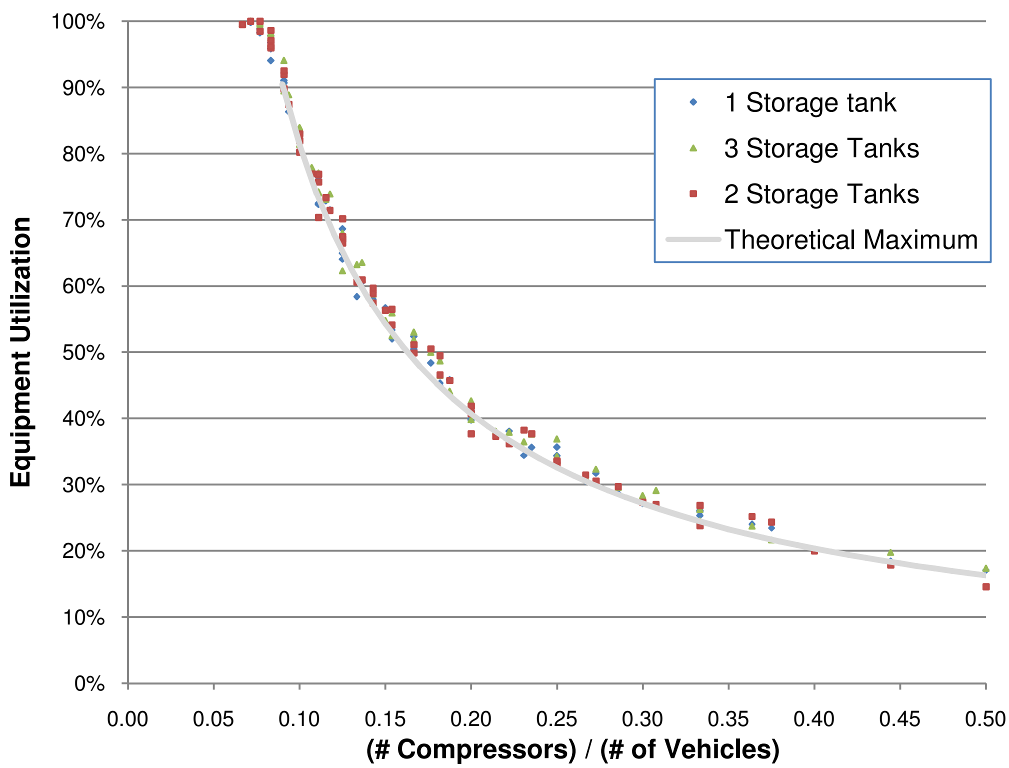


Figure 6.13 Compressor to Vehicle Ratio versus Utilization

There is a maximum utilization which can be achieved before the “quick fill” condition is violated for a given configuration of components. The approximate maximum utilization is estimated using the model and are given in Table 25.

Table 25 Approximate Maximum Utilization

Number of compressors	Number of Storage Tanks	Maximum Utilization
1	1	0.26
	2	0.34
	3	0.55
2	1	0.41
	2	0.57
	3	0.67
3	1	0.46
	2	0.56
	3	0.67
4	1	0.59
	2	0.70
	3	0.77

It is not practical to select a system configuration which has a compressor utilization close to the maximum utilization found in Table 25 because it will result in refueling times which are close to 30 minutes. The three-compressor configuration with three ground storage tanks and 22 vehicles is selected for analysis. It is recognized that quicker payback period are achievable, but given the time constraints of the large automotive manufacturer, this system will produce the most practical system with a reasonable payback period.

6.5.3.3 Number of Storage Tanks and Pumps

The next step in the process is to minimize the average refueling time by adjusting the number of vehicle storage tanks and dispensers. Figure 6.14 shows the average refueling time versus the number of dispensers for several different vehicle tank configurations. The three-tank vehicle configuration is shown for reference, but it is not practical due to the severely limited vehicle range. A minimum of 2 dispensers is also assumed.

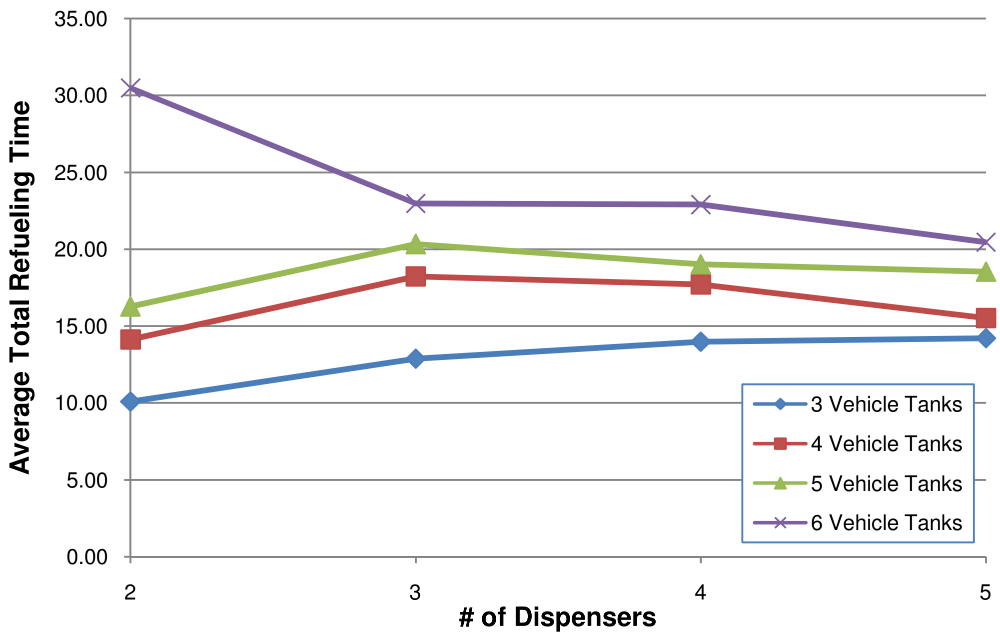


Figure 6.14 Number of Dispensers versus Refueling Time

It can be seen that four vehicle tanks and two dispensers will produce the fastest refueling times. The primary reason that the number of vehicle storage tanks and dispensers are not used in optimization for quickest payback period is because the effects that they have on the payback period is highly variable. Figure 6.15 shows the payback period for various configurations and it can be seen that there is no discernable pattern. Additionally, slight changes in initial conditions and the scheduling of the deliveries have an unpredictable impact on the payback period. This is predominately due to the changes in compressor utilization caused by inefficiencies caused when trucks try and refuel at the same time.

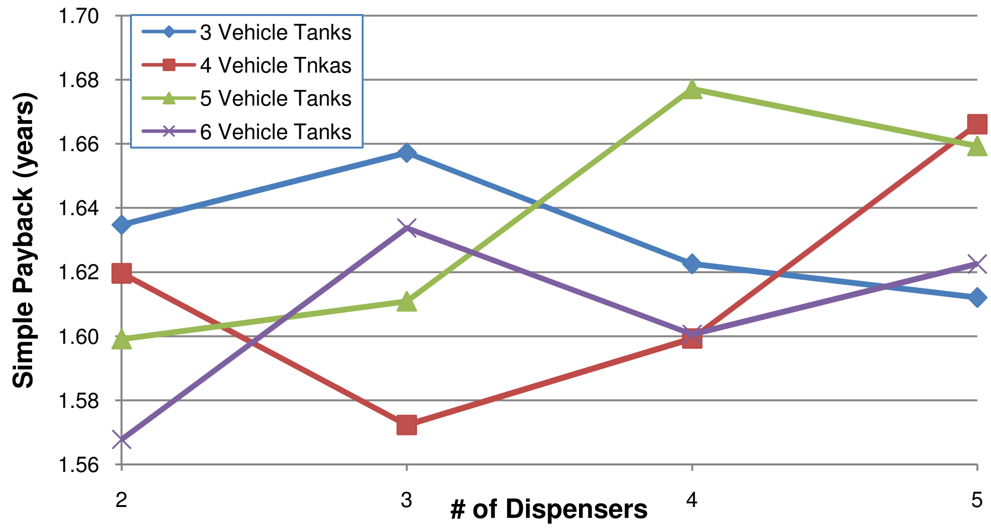


Figure 6.15 Number of Dispensers versus Simple Payback

6.5.3.4 Proposed Pilot Refueling Station

The optimal system for the large automotive manufacturer is found to be a three-compressor system with 3 storage tanks, 2 dispensers, 22 vehicles, and 4 storage tanks for each vehicle. The simulation results for this system configuration are shown in Table 26. This station requires a total capital investment of approximately 1.1 million dollars, but this investment is offset in the first year by a $448,000 tax credit associated with alternative fuel vehicles and a $30,000 thousand dollar tax credit for alternative refueling stations. Both of these tax credits, however, are set to expire after 2009. The annual economic savings realized by the on-site CNG refueling system is approximately $400,000 thousand dollars a year, which yields a simple payback period of 1.6 years. The annual TBL savings is approximately $685,000 thousand dollars, which yields a simple payback period of 0.93 years. These simple pay payback periods also incorporate a fuel tax credit which is also scheduled to expire in 2009. The sensitivity of these payback periods to tax incentives, as well as other model inputs, will be investigated in the next section. A detailed analysis of the revenue streams generated by this system is investigated in section 6.6.

Table 26 Proposed On-site CNG Refueling Station

Metric	Value	units
Total Compressor Capacity	300	scfm
Total Ground Storage	240	gal_{US} (3600 psi)
Number of Dispensers	2	
Number of Vehicles	22	
Maximum Vehcile Range	380	miles
ΔCost per Mile	0.25	$/mile
Value of ΔEmissions	0.13	$/mile
Miles per Vehicle	350	miles/day
Shipments per Vehicle	2.40	shipments/day
Average Refueling Time	13	min
Average Wait time	3	min
Total Capital Investment	1,114,500	$
Property tax credit	478,800	$/year
Annual Savings	400,746	$/year
Annual TBL Savings	685,540	$/year
TBL Simple Payback	**0.93**	**years**
Simple Payback	**1.59**	**years**

6.5.4 Model Sensitivity Analysis

6.5.4.1 Government Incentives

The government incentives for the use of alternative fuels and technology are currently defined in the Energy Policy Act of 2005, The Jobs Act, and the Federal Highway Bill. The specific tax incentives incorporated into the model include a tax credit for alternative fuel vehicles, alternative fuel refueling stations, and tax credit per DEG. These tax credits, however, are set to expire in 2009 so it is important to investigate the effect that this will have on the payback period if these incentives are not renewed.

The vehicle tax credit can either be 50% or 80% of the incremental cost of an alternative fuel vehicle depending on the emissions rate of the vehicle. The NGV chosen for this analysis meets 2010 EPA standards for HDDV, which should qualify them for the 80% tax credit. It is important, however, to investigate the impact of only a 50% or 0% vehicle tax credit. The alternative fuel tax credit for natural gas is currently .50 cents per DEG, which represents a significant portion of the savings currently realized by CNG use. The refueling station tax credit is currently capped at $30,000. Compared to the total capital investment required for the refueling station, this tax is not likely to have a large impact on the payback period. Table 27 shows the effect on the payback period of several different tax scenarios.

Table 27 Effect of Tax Incentives on Simple Payback

Senario	Simple Payback	% Change	TBL Simple Payback	% Change
No Facility Tax Credit	1.69	4%	0.99	4%
Only 50% Vehicle Tax Credit	2.15	33%	1.26	33%
No Vehicle Tax Credit	3.03	87%	1.77	86%
No Fuel Tax Credit	3.59	122%	1.40	47%
No Tax Credits	6.85	323%	2.67	181%

The impact of the tax credits on both the economic and TBL payback periods is significant. If no tax incentives are in place, the economic payback period more than doubles. The fuel tax credit has the largest impact on the payback period, followed by the vehicle tax credit, then the facility tax credit. If investments are made on a purely economic standpoint, these tax credits are essential because they keep the payback period under 2 years. A two year payback for a TBL analysis is possible without the tax credits, but these tax credits still play a crucial role in reducing the capital investment burden.

An interesting case to evaluate is the economic simple payback with the tax incentives, with a value of 1.6 years, versus the TBL simple payback without the incentives, with a value of 2.67 years. This differential indicates that government is paying a premium rate for emissions abatement or that the dollar values per ton of emissions are undervalued in this analysis.

6.5.4.2 Fuel Cost Ratio

The ratio between the cost of diesel and the cost of natural gas, on DEG basis, is not constant nor is it predictable. This ratio was discussed in detail in section 6.3.2. The standard eviation in the price ratio over the last ten years is approximately 0.10. The percent change in payback period versus the percent change in the fuel cost ratio is shown in Figure 6.16. An increase in the fuel cost ratio indicates an increase the price of natural gas relative to diesel and an increase in the number of years indicates an increase in the payback period.

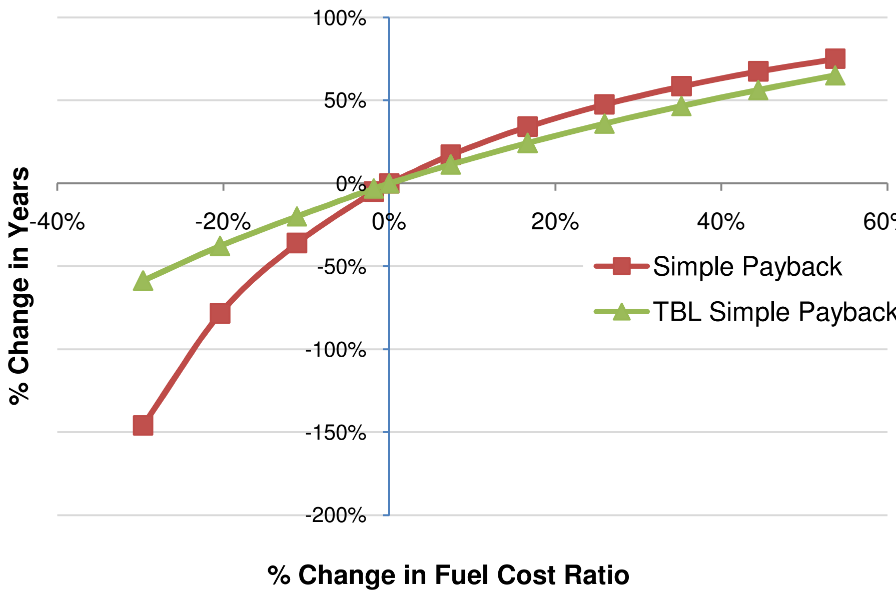


Figure 6.16 Simple Payback Sensitivity to Fuel Price Ratio

The model behaves as expected; since the annual savings are derived from a low fuel cost ratio, an increase in the fuel cost ratio causes an increase in the payback period. The TBL payback period is less sensitive to changes in the fuel cost ratio because a significant amount of annual savings are derived from emissions reduction. The fuel cost ratio is expected to remain relatively constant as discussed in section 6.3.2.

6.5.4.3 Value of Emissions Abatement

The dollar value associated with emissions abatement is discussed in detail in Chapter 5. The $/ton values which are used for each emission in the TBL are average values compiled from several studies. Table 28 shows the effect of varying the $/ton value for each emission by ± one standard deviation. If the standard deviation is higher than the average, a zero value is used for the low $/ton value.

Table 28 Variation in TBL Simple Payback due to Value of Emissions Abatement

Senario	Value of ΔEmissions	TBL Simple Payback	% Change
All $/ton +1std. Deviation	0.148	0.89	6.3%
All $/ton -1std. Deviation	0.084	1.11	-16.8%
CO $/ton +1std. Deviation	0.132	0.94	1.1%
CO $/ton = 0	0.127	0.96	-1.1%
NOX $/ton +1std. Deviation	0.161	0.86	9.5%
NOX $/ton -1std. Deviation	0.098	1.05	-10.5%
PM $/ton +1std. Deviation	0.139	0.92	3.2%
PM $/ton -1std. Deviation	0.119	0.98	-3.2%
SOX $/ton +std. Deviation	0.134	0.93	2.1%
SOX $/ton -std. Deviation	0.124	0.96	-1.1%
HC $/ton +std. Deviation	0.086	1.06	-11.6%
HC $/ton = 0	0.136	0.93	2.1%
CO2 $/ton +std. Deviation	0.133	0.94	1.1%
CO2 $/ton -std. Deviation	0.126	0.96	-1.1%

The dollar per ton value for NOx has the largest impact on the TBL simple payback, which is expected due to its high dollar value, and high gram per mile emissions. The HC also has a large impact on the TBL payback period when the +1 standard deviation case is examined. This is also expected due the excessively high standard deviation of the $/ton value and the high rate of HC emissions from natural gas vehicles. The $/ton values of the other emissions have negligible impact on the TBL simple payback within ± 1 standard deviation. The relative importance of NO_X and PM emissions is also demonstrated in the TBL payback sensitivity to changes in the gram per mile rate which is shown in Figure 6.17.

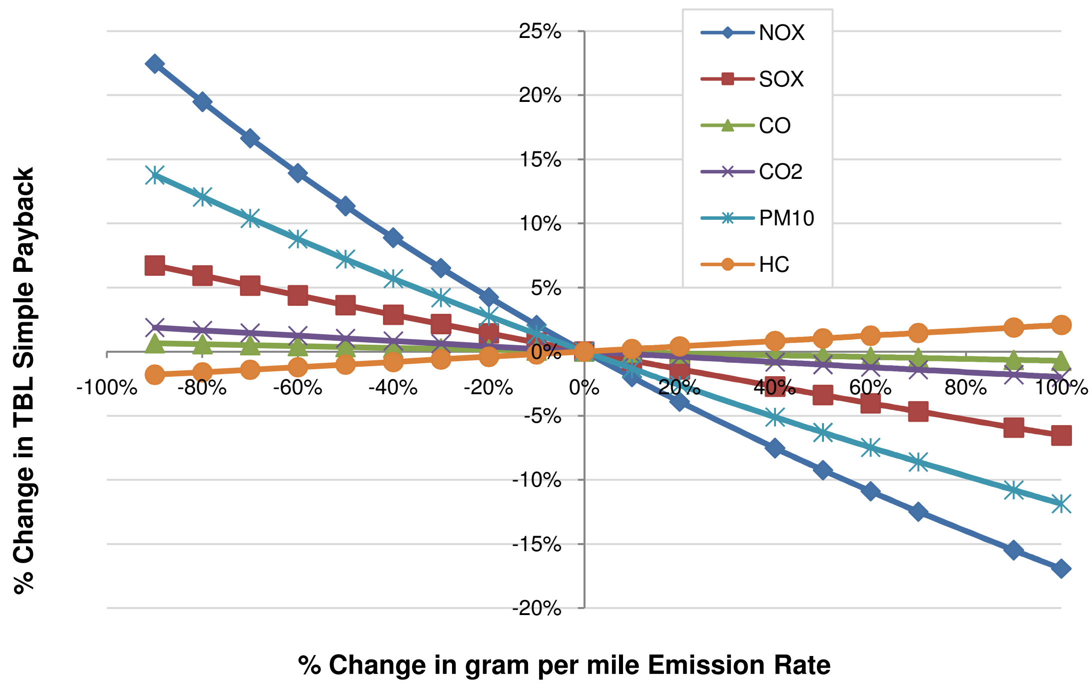


Figure 6.17 TBL Simple Payback Sensitivity to Gram per Mile Emission Rate

6.5.4.4 Diesel MPG

The diesel MPG used in the model is based on an average value obtained from the survey responses. The wide range in survey response, coupled with inaccurate reporting, indicate that there may be significant error in this value. The sensitivity of the payback period to changes in the diesel MPG is shown in Figure 6.18.

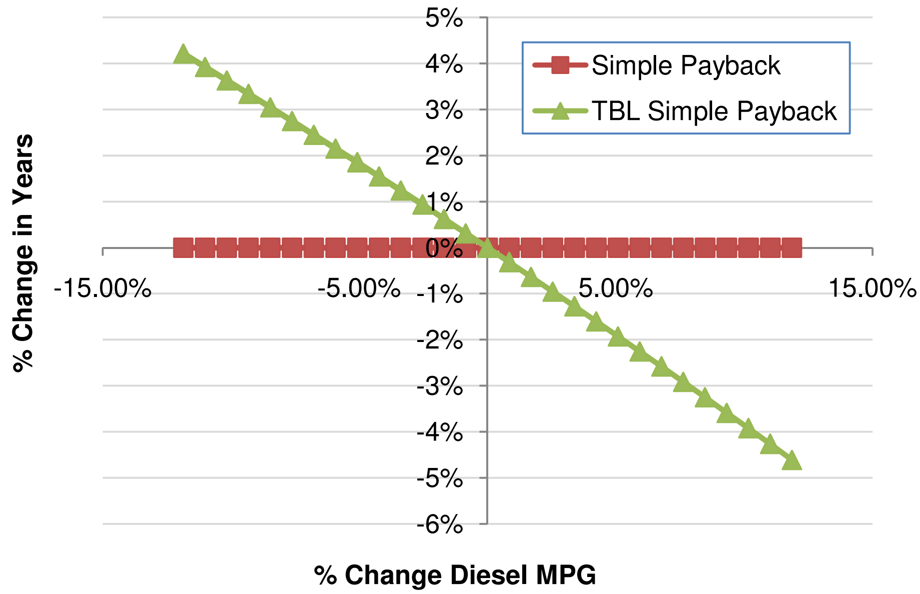


Figure 6.18 Simple Payback Sensitivity to Diesel MPG

Since the fuel mileage of a CNG is modeled using a flat penalty, changing the diesel mpg changes the CNG mileage as well. Savings are based on the change in cost per mile and the number of miles traveled, but changing the fuel mileages of the vehicles will have equal and opposite impacts on these metrics. Increasing the diesel mpg, for example, will decrease the fuel saving per mile, but increase the number of miles which can be driven in a year. This effect explains why the economic payback period is insensitive to changes in diesel mpg and exposes a limitation of the model. The TBL payback period is affected because the gram/mile emission rates are not altered to reflect the change in efficiency. When the diesel mpg is increased, the total number of miles driven per year also increases but the emissions rates are not reduced unless the MOBILE6 model is altered. Increasing the miles per year also increases the TBL savings per year which, in turn, reduces the TBL simple payback. Because of the limitation of the model, it should not be used to investigate the effects of changes in diesel mpg. The effects of changing the CNG vehicle mileage, however, can be investigated by varying the magnitude of the of the fuel economy penalty. The fuel economy of diesel vehicles is expected to decrease in the immediate future due to the implementation of emissions equipment needed to reach 2010 emissions requirements. The mpg for both natural gas and diesel vehicles is expected to increase due to advancement in technology.

6.5.4.5 Natural Gas Penalty

The sensitivity of the payback period to changes in the CNG fuel economy penalty is shown in Figure 6.19. An increase in the fuel economy penalty represents a decrease in the expected mpg of CNG vehicles. The literature review indicated that the CNG fuel economy penalty could range from 10% to 25%, depending on age of equipment, technology, load, drive cycle, and vehicle type. The penalty is set at 15% for the TBL analysis because newer CNG technology has made significant improvements in efficiency.

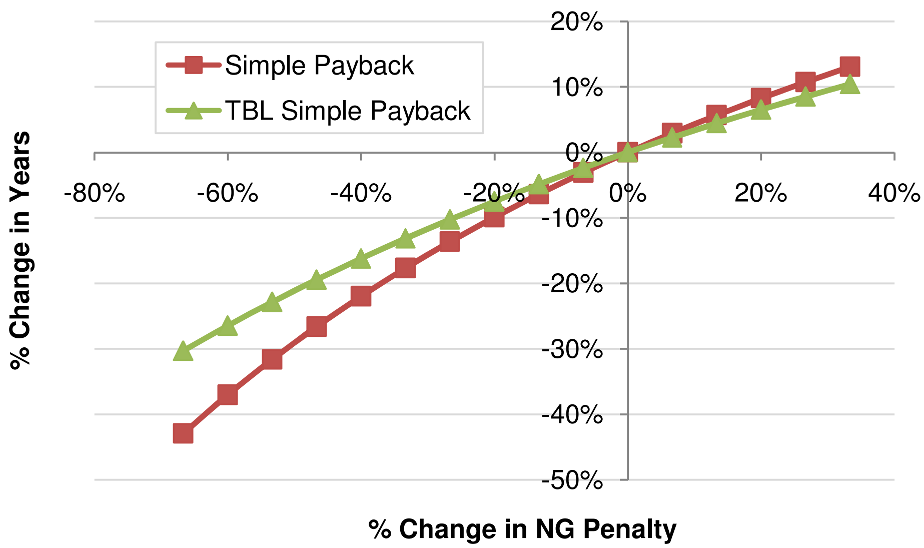


Figure 6.19 Simple Payback Sensitivity to the Natural Gas MPG Penalty

The model behaves as expected; an increase in the fuel economy penalty causes an increase in the payback period and vice versa. It appears that the NG penalty affects the economic simple payback more than the TBL payback, but this is not conclusive due to limitations of the model. The baseline emissions rates are derived from MOBILE6 in grams per mile, and the expected reduction in tailpipe emissions is also related on a per mile basis. The inherent reduction in NG mileage is already incorporated into these rates and is not adjusted by the parameter in the model. In order to properly investigate the effects of altering the CNG penalty on TBL payback period, it would be necessary to alter the model to have baseline emission rates and expected reductions on a per gallon basis. The natural gas penalty is expected to decrease as advancements in technology close the gap between diesel and natural gas mpg. There will always, however, be a natural gas mileage penalty due to the low compression ratio of the engine.

6.5.4.6 Installation Cost

The installation cost is assumed to be predominately comprised of a percentage of the equipment cost, but there is a great deal of uncertainty regarding because every facility and/or location will have drastically different design, fabrication, and transportation costs. The sensitivity of the payback schedule to changes in the installation cost is shown in Figure 6.20. Even large variations in installation cost have a small impact on the payback period because it is relatively small portion of the total capital costs when compared to the equipment cost of the facility and the incremental costs of the vehicles.

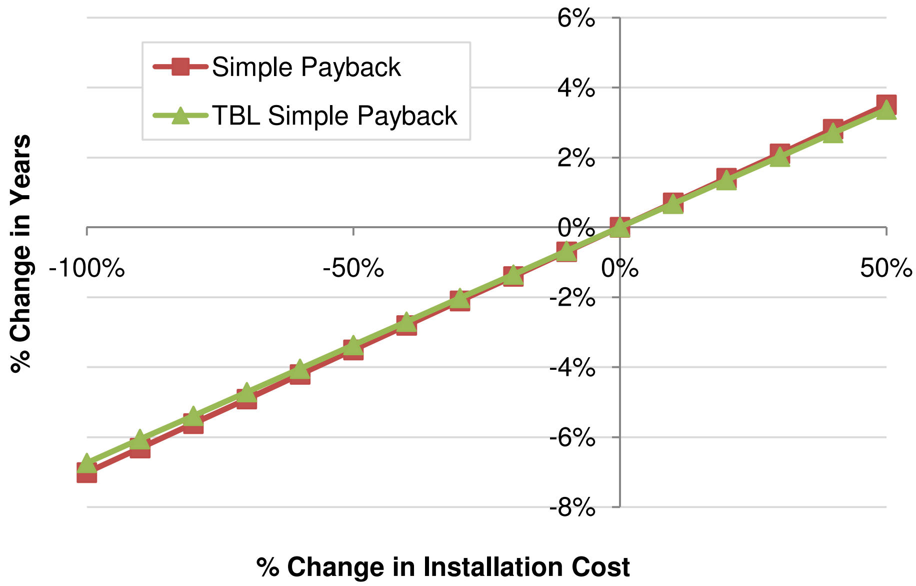


Figure 6.20 Simple Payback Sensitivity to Installation Cost

6.5.4.7 Facility Maintenance Costs and Insurance

The facility maintenance and insurance cost are estimated in a similar manner to the installation costs and suffer from the same uncertainty. The sensitivity of the payback period to changes in facility maintenance and insurance is shown in Figure 6.21. Since this cost is annual, the change in the payback period can be significant and the effect on the revenue streams over the useful lifetime of the facility will be even greater.

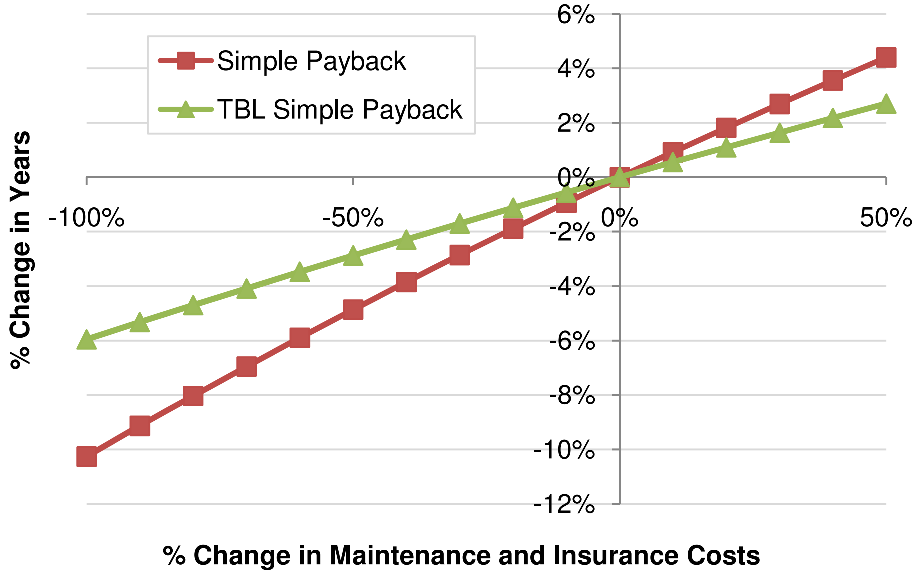


Figure 6.21 Simple Payback Sensitivity to Maintenance and Insurance Costs

6.5.4.8 Fuel Tank Cost

The cost of fuel tanks represents a majority of the incremental vehicle cost for CNG vehicles. The sensitivity of the payback period to changes in fuel tank cost is shown in Figure 6.22. The total fuel tank cost is currently estimated to be $16,000 dollars for each vehicle, but this cost is currently offset by large government tax credits. Increasing the cost of the fuel tanks increases the payback period a marginal amount. If the government incentives are not in place, the effect of the fuel tank cost will be dramatically increased.

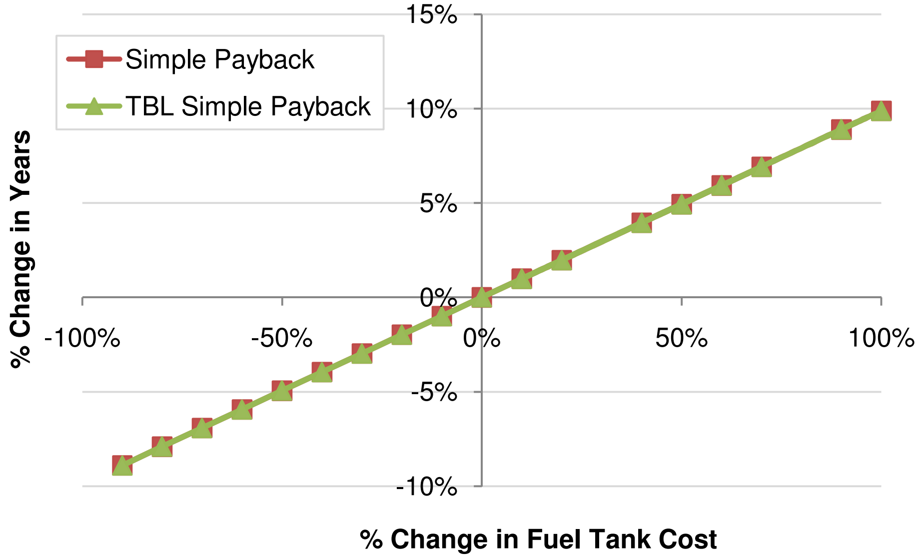


Figure 6.22 Simple Payback Sensitivity to Fuel Tank Cost

6.5.4.9 Vehicle Maintenance Cost

The incremental vehicle maintenance is the cost increase associated with maintaining a CNG vehicle versus a standard diesel vehicle. The payback sensitivity to changes in maintenance costs is shown in Figure 6.23. The incremental vehicle maintenance cost has a substantial impact on the payback period

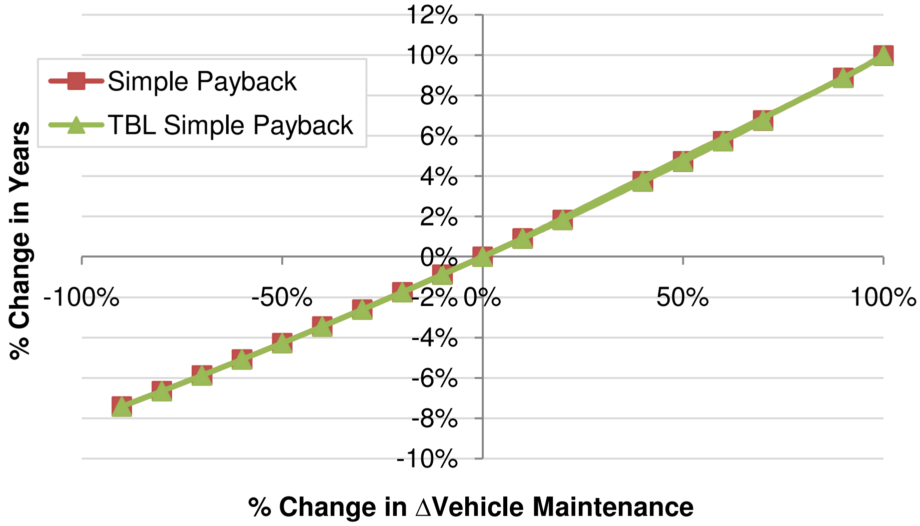


Figure 6.23 Simple Payback Sensitivity to ∆Vehicle Maintenance Cost

6.5.4.10 Monte-Carlo Uncertainty Analysis

A Monte-Carlo uncertainty analysis is performed to estimate the cumulative impact of the most uncertain variables. The uncertain variables considered in this analysis are the installation costs, insurance cost, maintenance costs, natural gas fuel economy penalty, vehicle tank cost, incremental engine cost, incremental vehicle maintenance cost, and the fuel cost ratio. The expected change in tailpipe emissions and the dollar value of emissions abatement for NO_X, SO_X, CO, CO_2, PM, and HC are also considered. Since there is little information on the expected distribution of these variables, a uniform distribution is selected to represent the uncertainty using the maximum and minimum values. Table 29 shows the uncertain variables used in the analysis and the expected maximum and minimum values. One hundred thousand trials are run for the Monte-Carlo simulation, and the results are shown in Figure 6.24 and Figure 6.25 for the economic and TBL simple payback respectively.

Table 29 Variables used in the Uncertainty Analysis

Uncertain Variable	Low Value	High Value
Desing and Installation Cost (as a percenaget of equipment cost)	5%	15%
Natural Gas Fuel Economy Penalty	10%	25%
Insurance and Maintenance Cost (as a percentage of equipment cost)	5%	15%
Vehicle Tank Cost	$3,000	$5,000
Incremental CNG Engine Cost	$0	$2,000
Incremental Vehicle Maintenance Cost	$0	$4,000
Diesel vs. NG Fuel Cost Ratio (DEG Basis)	0.35	0.60
NOX -Percent Reducition inTailpipe Emissions	27%	45%
SOX -Percent Reducition inTailpipe Emissions	98%	100%
CO -Percent Reducition inTailpipe Emissions	84%	93%
CO2 -Percent Reducition inTailpipe Emissions	3%	60%
PM10 -Percent Reducition inTailpipe Emissions	90%	95%
HC -Percent Reducition inTailpipe Emissions	0%	1000%
NOX -Dollar Value per ton of Emissions Abatement	$0	$24,000
SOX -Dollar Value per ton of Emissions Abatement	$0	$70,000
CO -Dollar Value per ton of Emissions Abatement	$0	$1,775
CO2 -Dollar Value per ton of Emissions Abatement	$0	$30
PM10 -Dollar Value per ton of Emissions Abatement	$0	$150,000
HC -Dollar Value per ton of Emissions Abatement	$0	$70,000

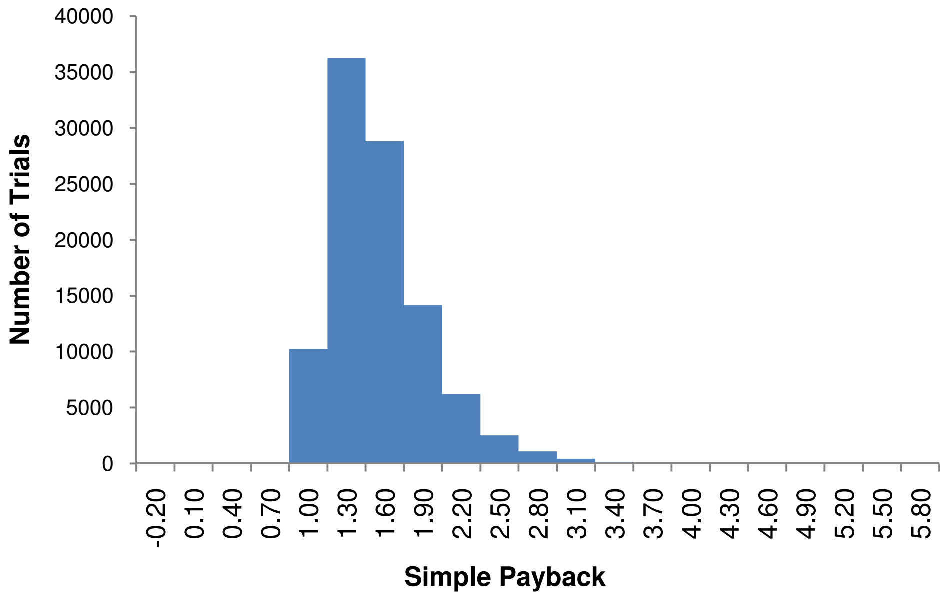


Figure 6.24 Histogram of the Monte-Carlo Simulation Results for Simple Payback

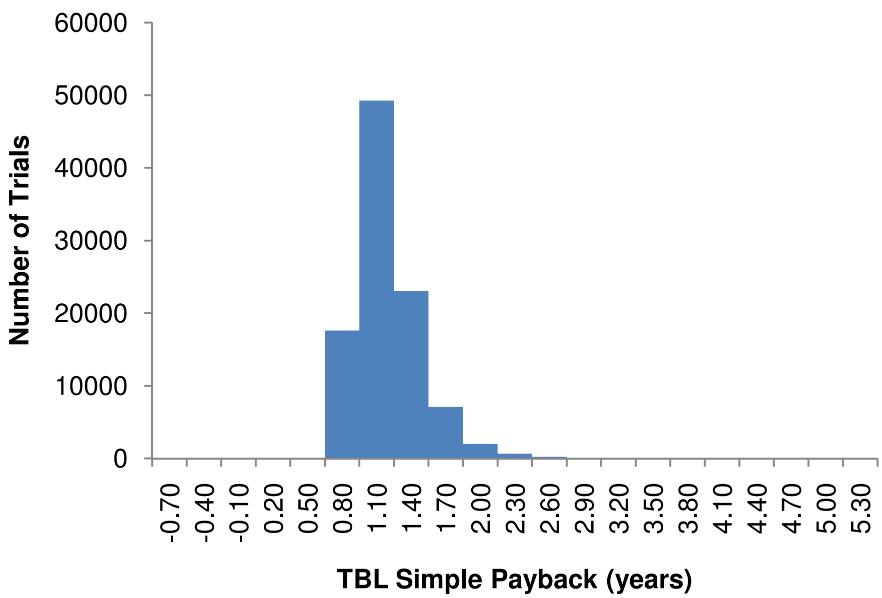


Figure 6.25 Histogram of the Monte-Carlo Simulation Results for TBLSimple Payback

The statistics for the Monte-Carlo simulation are also shown in Table 30. It can be seen that the average economic simple payback is 1.4 years with a standard deviation of approximately 0.4 years. This indicates that the 1.6 year economic simple payback calculated in the previous section is a conservative estimate. The average TBL simple payback is 1.0 years with a standard deviation of 0.3 years. This indicates that 0.93 TBL simple payback predicted in the previous section is slightly liberal. It is expected that the economic simple payback is conservative because high estimates of equipment costs are intentionally chosen to ensure that they are not underestimated. The liberal TBL simple payback estimate is most likely due to the wide variation in the literature values used for the percent change in tailpipe emissions and the dollar value of emissions abatement.

Table 30 Monte-Carlo Uncertainty Analysis results

Statistic	Simple payback (years)	TBL Simple Payback (years)
Mean	1.41	1.04
Number of Trials	100,000	100,000
Standard error	0.001	0.001
Minimum	0.726	0.50
Maximum	5.231	4.73
Median	1.329	0.99
Range	4.506	4.22
Standard Deviation	0.386	0.29
Variance	0.149	0.08
Skewness	1.345	1.68
Kurtosis	5.842	8.98

6.5.5 Revenue Streams

The economic and TBL simple payback periods provide a convenient way to quickly access and optimize a system configuration, but the revenue streams must be evaluated over the useful lifespan of the equipment to get a clear picture of the investment opportunity. Assuming that the refueling facility and vehicles have a ten year useful lifespan, Figure 6.26 shows the revenue streams for the proposed refueling station. This revenue stream incorporates all current tax incentives and assumes that they expire as scheduled. Inflation is not considered in the revenue streams, so all income and expenditures are given in real 2008 dollars. The fuel cost ratio is also assumed to be fixed at the current value.

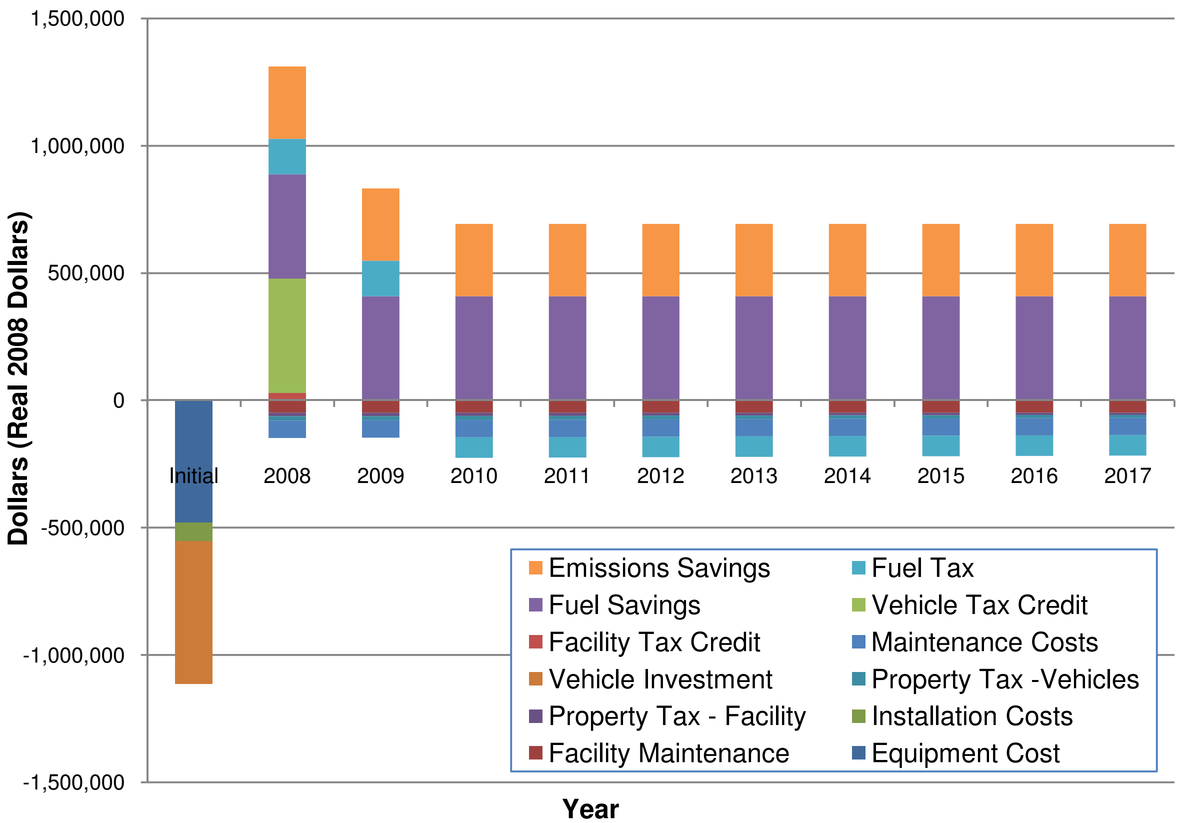


Figure 6.26 Revenue Stream for Proposed On-site Refueling Station

The revenue stream under these assumptions is extremely favorable. The large tax incentives quickly offset the large capital investment and the fuel cost ratio provides a positive yearly income.

6.5.5.1 Tax Incentive and Fleet Turnover Scenarios

Tax incentives may be unavailable, or expired, at the time of investment which will have an enormous impact on the capital investment and revenue streams. This impact is especially profound if the vehicle lifespan, also referred to as vehicle turnover rate, is significantly less than 10 years.

Table 31 shows the economic and TBL internal rate of return for three different fleet turnover rates under three different tax scenarios. It is important to note that CNG vehicles are assumed to have the same resale value as equivalent diesel vehicles. It is also assumed that that the vehicle tax credit will not be renewed under any scenario.

Table 31 Net Present Value and Internal Rate of Return.

Tax Incentive Senario	Vehicle Life Span	IRR	
		Economic	TBL
No Tax Incentives	10	11%	41%
	5	3%	36%
	3	-7%	33%
Fuel Tax Incentive Expires in 2010	10	36%	73%
	5	30%	71%
	3	18%	66%
Fuel Tax Incentive is Renewed	10	50%	81%
	5	45%	78%
	3	41%	75%

Without tax incentives, the economic IRR is only 11% even under the best fleet turnover scenario. An IRR of 11% is not likely to be sufficient given the level of capital investment and risk associated with this investment. Under the current tax codes, tax incentives will expire in 2010. The economic IRR under this scenario is very favorable under the 10 year, and 5 year fleet turnover rate and even under the 3 year fleet turnover rate, the IRR is 18% which may be compelling enough to produce investment. If the fuel tax incentive is renewed, the economic IRR is favorable for all fleet turnover scenarios. The TBL IRR is favorable under all fleet turnover and tax incentives. An interesting case to examine is the TBL IRR for the scenario without tax incentives versus the economic IRR for the other two tax scenarios. If the tax incentives expire, the economic IRR is less than the baseline TBL IRR. If the tax incentives continue, the economic IRR is greater than the baseline TBL IRR.

6.6 Onsite CNG Summary and Conclusion

An on-site CNG refueling system provides substantial reductions in operational costs and tailpipe emissions for truckload carriers. The price ratio between equivalent amounts of diesel and natural gas, on an energy basis, provides a tremendous opportunity for fuel cost savings if the natural gas is purchased from utility companies and compressed onsite. There is a significant amount of capital investment required for a CNG refueling station and CNG vehicles, but this cost is offset by government tax incentives. With the incentives in the current tax code, the simple payback for the proposed refueling station is 1.6 years with an IRR of 36%. Without the tax incentives, the simple payback is 6.9 years with an IRR of 11%. Given the inherent risk involved, tax incentives are crucial for the CNG business case if it is viewed purely from an economic standpoint.

With the incentives in the current tax code, the TBL simple payback for the proposed refueling station is 0.9 years with an IRR of 73%. The purpose of alternative fuel tax credits, however, is to subsidize environmental and social benefits of alternative fuels and promote their use. A TBL business case including tax incentives may count the value of the emissions savings twice. The TBL simple payback without tax incentives is 2.67 years with an IRR of 43%, which is still overwhelmingly positive.

The economic business case with tax incentives is one year faster, than the TBL business case without tax incentive. This indicates that either the government is paying a premium for economic and social benefits in an effort to encourage their use or that the dollar values used for emissions abatement in the TBL business case are too small. The fuel tax credit, however, is currently set to expire during the useful lifespan of the facility which explains why the IRR of the TBL analysis is still 10% higher despite having a higher payback period. Since the IRR is a better metric for the strength of a business case, the TBL analysis still provides an improvement to the CNG business case even if taxes incentives are not included.

Even though the economic and TBL business cases for on-site CNG facility and vehicles are extremely favorable, the technology is extremely limited. The drastic reduction in vehicle range limits CNG to short haul shipping lanes. Shipping lanes are also limited to those which originate or terminate near the central refueling station. The large automotive manufacturer has an abundance of qualifying lanes because of high volumes of shipments between manufacturing facilities which are located in close proximity. The extent to which this system can be expanded is still unknown. Since this analysis is based on dedicated CNG vehicles, the business case would not apply to truckload carriers which do not have a guaranteed supply of short haul business.

CHAPTER 7 CRITICAL EVALUATION AND CONCLUSIONS

7.1 Method Validation

It is important to assess its validity of a method in order to help assess its usefulness. The Validation Square shown in Figure 7.1 is a tool that can guide the evaluation of the validity of a proposed method (Pedersen, et al., 2000). A brief overview of each region of the validation square is given below.

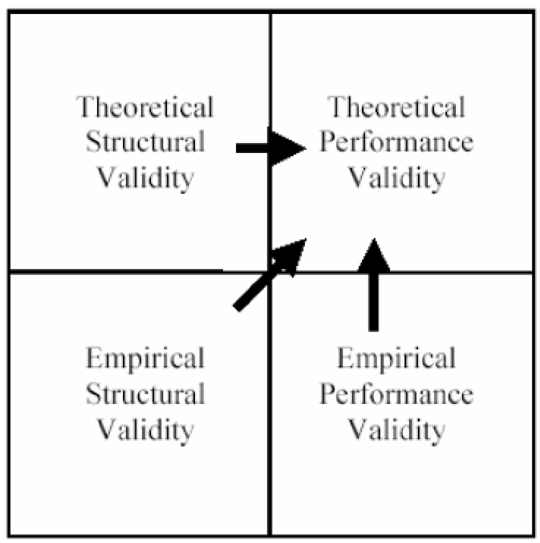


Figure 7.1 The Validation Square

Theoretical Structural Validity deals with the internal consistency of the design method and its logical soundness as a whole. Empirical Structural Validity is the appropriateness of the example problem that has been used to test the method. Empirical Performance Validity is the ability of the method to produce appropriate results for the chosen example problems. The last region of the Validation Square is Theoretical Performance Validity which is the ability of the method to produce results for applications beyond the chosen example problems. This last region cannot be proven explicitly or empirically; it must be assumed based on the success of the proposed method for each of the other regions and the method's ability to produce useful results over a broad range of applications (Pedersen, et al., 2000). In the following sections discuss the performance of model with regard to each region in the validation square and are initiated by posing appropriate question for that region.

7.1.1 Theoretical Structural Validity

Does each of the steps in the method make sense by themselves and do the steps fit together in a logical manner?

The steps in this proposed method follow a logical path which is generally described as: identifying alternatives, eliminating alternatives, evaluating alternatives, and creation of a Triple-Bottom-Line business case. The process of identifying alternatives is necessary because the proposed method assumes that only the target application, not the specific fuel or technology, has been defined. A broad literature survey from a variety of sources, including informal sources, is used to capture all possible alternatives for the target application or sufficiently similar applications. This step makes sense because it generates a large list of candidates, including new and emerging fuels and technologies which may be missed by reviewing only candidates which have been extensively tested and analyzed for the specific application. This step is incorporated into the literature review given in Chapter 2.

The process of eliminating alternatives is necessary to reduce the number of candidates which require analysis. A decision model is first used to define the potential impacts of switching to an alternative fuel or technology and to define the measures of effectiveness which will be considered in the TBL analysis. This step makes sense because it helps the decision maker to elicit preferences and requirements. The expected change in the impacts and measures of effectiveness derived in the decision model are compiled from the literature review and a direct survey of carriers. This step makes sense because it allows the decision maker to quickly eliminate candidates which will obviously not meet requirements and identify candidates which are likely to match their preferences. This step is incorporated into Chapter 3 and the decision model in Chapter 4.

The process of evaluating the alternatives is necessary to rank the candidates on their expected TBL performance without having to carry out a full analysis for each one. An index of their expected reduction in tailpipe emissions is developed, which makes sense because a majority of the social and environmental benefits of alternative fuels and technologies are derived from these reductions. The economic index for alternative fuels is developed based on the energy cost. This makes sense because it allows the potential change in fuel cost to be compared without the need to factor in differences in engine efficiencies. The economic index for alternative technologies is created based of the cost effectiveness of reducing emissions on a dollar per ton basis. It makes sense to evaluate the alternative technologies separate from alternative fuels because they are independent in most cases, i.e. hybrid technology can be powered by any alternative fuel. This step is incorporated into the index section in Chapter 4.

The creation of a TBL business case for the top performing candidates is necessary to capture all implications, penalties, and benefits of switching to an alternative fuel or technology. This step begins by modeling the emissions of the current application and assigning a dollar value per ton of each emission considered. The vehicle and facility requirements are defined and all necessary economic costs and tax implications are gathered from the literature review and direct contact with supplier. This makes sense because it will provide the most up to date economic analysis of the business case. The benefits derived from emissions reductions are then incorporated, which allows the business case to be evaluated on TBL basis. This makes sense because it also allow the economic and TBL case to be compared. It also allows for the system to be optimized for either economic or TBL performance as required by the decision maker. This step is incorporated into Chapter 5 and an example of a TBL is given in Chapter 6.

7.1.2 Empirical Structural Validity

Is the example problem appropriate?

The shipping and logistics network of the large automotive manufacturer is used as an example problem. Specifically, the inbound deliveries which originate either from component suppliers or deliveries between the company's manufacturing facilities are chosen as the target application. This example problem is appropriate because the target application is typically handled by vehicles powered by standard diesel engines and there is an abundance of alternative fuels and technologies available to replace or augment these engines. The size of the large automotive manufacturer's shipping and logistics network also provides enough economic opportunity to justify this investigation.

7.1.3 Empirical Performance Validity

Are useful results realized for the example problems?

An on-site compressed natural gas refueling system is identified by the proposed method as the candidate fuel which will most likely produce the best TBL business case for The large automotive manufacturer's application under current business conditions. The results of the method are useful because the TBL business case for the use on on-site CNG is overwhelming positive. Additionally, the TBL business strengthened the economic case by significant margin.

7.1.4 Theoretical Performance Validity

Can useful results be realized for applications beyond the chosen example problem?

This method can provide useful results for applications beyond the chosen example, which is indicated by the positive response to other three validation squares, but only if certain requirements are met. The application must be dominated by traditional fossil fuels, and there must be sufficient supply of alternative fuels or technologies available. There also must be enough information to accurately model the emissions of the applications and determine the expected reduction in emissions. Information on vehicle and facility requirements, limitations, and performance is also required.

7.1.5 Method Shortcomings and Future Work

7.1.5.1 Dollar Value of Emissions Abatement

The primary weakness of the TBL analysis is the dollar value of emissions abatement assigned to each criteria pollutant which is considered. The dollar per ton rate used in the analysis is the average value from several different studies, but there is a great deal of variation between each study. This is most likely due to the various methods, impacts, criteria and data used by each researcher. There is also a lack of data for certain pollutants, such as particulate matter and sulfur oxides. The estimates of emissions impacts were usually narrowly focused, however, so it is not likely that these values reflect the total potential value of reducing emissions. This indicates that this analysis is a fairly conservative estimate of the TBL benefits. Future work includes finding additional and more recent sources of information for the dollar value of emission abatement and the investigation of emissions permits and markets to set appropriate values.

7.1.5.2 Tax Incentives versus TBL analysis

This method does not attempt to resolve the potential conflict between tax incentives and the value of emissions abatement. If purpose of the dollars spent on tax incentives overlaps the rationale for damage costs considered, there is potential that the value of emission saving could be counted twice. If, for example, the government offers a tax incentives for alternative fuels and technologies in the hopes of improving air quality, it may not be appropriate to include the both the tax incentive and the derived benefits in the TBL analysis. This is less of an issue for some social benefits, such as energy security, which are not easily quantifiable and not included in the studies of emissions abatement. This method evaluates the TBL business case of the alternative fuel with, and without, the tax incentives to avoid this issue. This approach also allows for interesting comparisons between the tax incentives offered and the potential benefits derived from emissions reduction. Future work includes in depth research regarding the legislative purposes behind the tax credits and development of a method to adjust the dollar value associated with emission abatement to avoid double counting of benefits.

7.1.5.3 Variability in Fuel Costs

This method does not have a provision for estimating and accounting for the variability in fuel costs over the time span considered. The TBL business case which is proposed by this method is incremental and the margin between the price of alternative fuels and diesel is assumed to be constant. This assumption is generally valid for the fuel costs averaged over a long periods of time, but short term fluctuations in fuel prices may a large impact on the revenue streams and internal rate of return realized in the TBL business case. Future work includes modeling the uncertainty involved in the fuel prices and performing an uncertainty analysis for the entire business model.

7.1.5.4 Implementation Guidance

Implementation guidance is essentially the logistics behind actually selecting individual shipments or trucks to run the alternative fuel and can also include other variables such as infrastructure location. The proposed method does not provide any guidance for implementation of the alternative fuel or technology primarily because the level of effort required and the complexity involved varies tremendously form one alternative fuel or technology to another. The logistical effort is also highly dependent on the application selected, and the company involved in the business case. The TBL business case for on-site CNG developed for the large automotive manufacturer required significant effort to find a suitable location for the refueling equipment and identify suitable shipping lanes, especially because of the severe range restrictions .

7.2 Closure

Alternative fuels and technologies for truckload carriers can provide significant environmental and social benefits over traditional heavy duty diesel vehicles by reducing petroleum-based fuel consumption and vehicle tailpipe emissions. These alternative fuels and technologies, however, often carry a cost premium or require significant capital investment. Dedicating vehicles, equipment, and infrastructure to an alternative fuel or technology also represents a significant risk in the extremely volatile trucking business. A Triple-Bottom-Line analysis, which includes economic, social, and environmental impacts of an alternative fuel or technology will strengthen the business case by incorporating the benefits of emissions reduction.

The method for identifying alternative fuels and technologies which is proposed in this thesis indentified on-site CNG as the alternative fuel which would provide the best TBL for the large automotive manufacturer's application. An on-site CNG refueling system provides substantial reductions in operational costs and tailpipe emissions for truckload carriers. There is a significant amount of capital investment required for a CNG refueling station and CNG vehicles, but this cost is offset by government tax incentives.

With the incentives in the current tax code, the simple payback for the proposed refueling station is 1.6 years with an IRR of 36%. Without the tax incentives, the simple payback is 6.9 years with an IRR of 11%. Given the inherent risk involved, tax incentives are crucial for the CNG business case if it is viewed purely from an economic standpoint. With the incentives in the current tax code, the TBL simple payback for the proposed refueling station is 0.9 years with an IRR of 73%. The purpose of alternative fuel tax credits, however, is to subsidize environmental and social benefits of alternative fuels and promote their use. A TBL business case including tax incentives may count the value of the emissions savings twice. The TBL simple payback without tax incentives is 2.67 years with an IRR of 43%, which is still overwhelmingly positive.

The economic business case with tax incentives is one year faster, than the TBL business case without tax incentive. This indicates that either the government is paying a premium for economic and social benefits in an effort to encourage their use, or the dollar values used for emissions abatement in the TBL business case are too small. The fuel tax credit, however, is currently set to expire during the useful lifespan of the facility which explains why the IRR of the TBL analysis is still 10% higher despite having a higher payback period.

Since the IRR is a better metric for the strength of a business case, the TBL analysis still provides an improvement to the CNG business case even if taxes incentives are not included.

APPENDIX A – MOBLE6 CODE

```
*<----Start Header Section
MOBILE6 INPUT FILE :
*Identifies a M6 input file as a regular command input file rather than a batch file
POLLUTANTS         : NOX CO CO2 HC
*Controls which pollutants will be calculated
PARTICULATES       : SO4 SO2
*Enables the computation of particulate matter
SPREADSHEET        :
* average calendar year emission factors in a form suitable for spreadsheet
RUN DATA           :
*Marks end of Header section and beginning of Run section
*<----Start Run Section
NO REFUELING       :
*Allows user to exclude refueling emissions from all output values.
EXPRESS HC AS THC  :
*Directs M6 to output exhaust HC as THC
EXPAND HDDV EFS    :
*Directs M6 to display EFs by 8 HDDV classes
EXPAND HDGV EFS    :
*Directs M6 to display EFs by 8 HDGV classes
EXPAND EXHAUST     :
*Specifies that start, running, and total exhaust EFs be displayed in descriptive output.
IDLE PM EMISSIONS  :
*Displays idle mode particulate emission factors for heavy-duty diesel vehicle classes 2b-8b
MIN/MAX TEMPERATURE: 60. 60.
*Specifies minimum and maximum daily temperatures
REG DIST           : REGDATA.D

SCENARIO REC       : Short Haul
*Allows user to label individual scenario results
CALENDAR YEAR      : 2007
```

```
FUEL RVP           : 9.0

*Required input of average gasoline Reid vapor pressure

PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV PMDDR1.CSV PMDDR2.CSV

*Specifies the location of the data files that contain the particulate emission factors.

PARTICLE SIZE      : 10.0

*Allows the user to specify the maximum particulate size cutoff (PSC) that is used by the model.

DIESEL SULFUR      : 300.00

VMT BY FACILITY    : FVMTS.def


SCENARIO REC       : Medium Haul

CALENDAR YEAR      : 2007

FUEL RVP           : 9.0

PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV PMDDR1.CSV PMDDR2.CSV

PARTICLE SIZE      : 10.0

DIESEL SULFUR      : 300.00

VMT BY FACILITY    : FVMTM.def


SCENARIO REC       : Long Haul

CALENDAR YEAR      : 2007

FUEL RVP           : 9.0

PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV PMDDR1.CSV PMDDR2.CSV

PARTICLE SIZE      : 10.0

DIESEL SULFUR      : 300.00

VMT BY FACILITY    : FVMTL.def

END OF RUN         :
```

APPENDIX B – VISUAL BASIC CODE

```
Private Sub CommandButton1_Click()
Data1 = 225

Do

Timer_Step
Storage_Tank_Fill (Range("D19"))
Lane_Sweep
Move_que
Wait_Time
Refuel

Data_dump (Data1)
Data1 = Data1 + 1


Loop While Range("I14") < Range("D20")

Analize
End Sub

Sub Timer_Step()
Range("I19") = Range("I19") + Range("D19")
If Range("K14") < 60 Then
    Range("K14") = Range("K14") + Range("D19")
    Else
        If Range("J14") < 23 Then
        Range("J14") = Range("J14") + 1
        Range("K14") = Range("D19")
        Else
        Range("I14") = Range("I14") + 1
     Range("J14") = 0
     Range("k14") = Range("D19")
     End If
    End If
End Sub

Sub Storage_Tank_Fill(min)
If Range("I15") < Range("D16") * 0.9 Then
Range("I15") = Range("I15") + Range("D13") * min
Else
Range("D3") = Range("D3") + min
End If
End Sub

Sub Burn_fuel(index)
Worksheets("Refueling Time").Cells(index, 21).Value = Worksheets("Refueling Time").Cells(index,
21).Value - (Range("D21") * Worksheets("Refueling Time").Cells(index, 15).Value * 2 +
Worksheets("Refueling Time").Cells(index, 25).Value)
End Sub

Sub Que(index) 'Makes a que based on arrival time

    Range("D9") = Range("D9") + 1 'Keeps track of the number of deliveries

    If Worksheets("Refueling Time").Cells(index, 21).Value < -100 Then 'If truck needs gas, adds
    Worksheets("Refueling Time").Cells(index, 22).Value = Range("I18")
    Range("I18") = Range("I18") + 1
    End If

End Sub

Sub Lane_Sweep() 'Goes Through the list of lanes and creates a que and takes fuel at the app.
time

counter = 25
```

```
Do Until Worksheets("Refueling Time").Cells(counter, 2).Value = ""

    If Worksheets("Refueling Time").Cells(counter, 11).Value = Range("L14") Then

    Burn_fuel (counter)
    Que (counter)

    End If

counter = counter + 1
Loop

End Sub


Sub Move_que() 'Determines if it is possible/moves que foreward

Begin:
placeholder = Range("I17")

Do Until Range("I16") = Range("D17")  'Goes until all pumps are full



counter2 = 25


    Do Until Worksheets("Refueling Time").Cells(counter2, 2).Value = "" 'Cycles through lanes

        If Range("I17") = Worksheets("Refueling Time").Cells(counter2, 22).Value Then 'Checks to
see if que matches lane

            Range("I16") = Range("I16") + 1
            Range("I17") = Range("I17") + 1


            GoTo Begin

        End If

    counter2 = counter2 + 1
    Loop

Exit Do
Range("I17") = placeholder


Loop


End Sub

Sub Wait_Time() 'Adds wait time to vehicles in que not being serviced

counter4 = 25

Do Until Worksheets("Refueling Time").Cells(counter4, 2).Value = ""

    If Worksheets("Refueling Time").Cells(counter4, 22).Value > Range("I17") Then

    Worksheets("Refueling Time").Cells(counter4, 26).Value = Worksheets("Refueling
Time").Cells(counter4, 26).Value + Range("D19")


    End If

counter4 = counter4 + 1
Loop

End Sub
```

```
Sub Refuel()


pumps = Range("I16")

If Range("I16") = 0 Then
GoTo Skip_refuel
End If

Fast_Rate = 15 / Range("I16")
Slow_Rate = Range("D13") / Range("I16")


Do Until pumps = 0

counter5 = 25

    Do Until Worksheets("Refueling Time").Cells(counter5, 2).Value = "" 'Cycles through lanes

        If (Range("I17") - pumps) = Worksheets("Refueling Time").Cells(counter5, 22).Value Then
'Matches Que number to currently serving

            If Range("I15") < 0.2 * Range("D16") Then 'IF Storage is low, fuel at slow rate

                Worksheets("Refueling Time").Cells(counter5, 21).Value = Worksheets("Refueling
Time").Cells(counter5, 21).Value + Slow_Rate * Range("D19")
                Range("I15") = Range("I15") - Slow_Rate * Range("D19")

            Else 'If storage is full, fuel at fast rate

                Worksheets("Refueling Time").Cells(counter5, 21).Value = Worksheets("Refueling
Time").Cells(counter5, 21).Value + Fast_Rate * Range("D19")
                Range("I15") = Range("I15") - Fast_Rate * Range("D19")

            End If


            Worksheets("Refueling Time").Cells(counter5, 24).Value = Worksheets("Refueling
Time").Cells(counter5, 24).Value + Range("D19") 'Adds refueling time


            If Worksheets("Refueling Time").Cells(counter5, 21).Value > -15 Then 'Opens up a pump
is tank is 95% full
                Range("I16") = Range("I16") - 1
                Worksheets("Refueling Time").Cells(counter5, 23).Value = Range("L14")

            End If

        End If




    counter5 = counter5 + 1
    Loop

pumps = pumps - 1

Loop

Skip_refuel:

End Sub



Sub Data_dump(data)

Worksheets("Refueling Time").Cells(data, 1).Value = Range("I14") 'Day
Worksheets("Refueling Time").Cells(data, 2).Value = Range("L14") 'Time
Worksheets("Refueling Time").Cells(data, 3).Value = Range("I16") 'Pumps
```

```
Worksheets("Refueling Time").Cells(data, 4).Value = Range("I17") 'Que
Worksheets("Refueling Time").Cells(data, 5).Value = Range("I18") 'Next que
Worksheets("Refueling Time").Cells(data, 6).Value = (Range("I19") - Range("D3")) / Range("I19")
'%Compressor
Worksheets("Refueling Time").Cells(data, 7).Value = Range("I15") / Range("D16") '%Mass
Worksheets("Refueling Time").Cells(data, 8).Value = Range("D4") 'Wait time
Worksheets("Refueling Time").Cells(data, 9).Value = Range("D5") 'Refuel Time
Worksheets("Refueling Time").Cells(data, 9).Value = Range("D5") 'Refuel Time
Worksheets("Refueling Time").Cells(data, 13).Value = Range("I20") '# of deliveries

End Sub




Sub Analize()

'Histogram for pump usage:
Application.Run "ATPVBAEN.XLA!Histogram", Range("$C$225:$C$1665"), Range("$K$225"),
Range("$J$225:$J$235"), False, False, False, _
        False

'Histogram for delivery schedule:
Application.Run "ATPVBAEN.XLA!Histogram", Range("$K$25:$K$216"), Range("$O$225"),
Range("$N$225:$N$272"), False, False, False, _
        False

'Histogram for delivery schedule:
Application.Run "ATPVBAEN.XLA!Histogram", Range("$W$25:$W$216"), Range("$Q$225"),
Range("$N$225:$N$272"), False, False, False, _
        False

End Sub
```

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